

EDITORS
PROF DR RAUL DSG CAMPILHO
DR. ERCAN BERBERLER

URBAN RESILIENCE: ENGINEERING STRATEGIES FOR BUILT ENVIRONMENT RISKS



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PROF DR RAUL DSG CAMPILHO · DR. ERCAN BERBERLER



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URBAN STORMWATER MANAGEMENT AND SUSTAINABLE APPROACHES IN THE CONTEXT OF CLIMATE CHANGE

Editors

Prof. Dr. Raul DSG CAMPILHO

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Preface

Water is not only an indispensable resource for sustaining life, but also a strategic environmental asset whose significance has become increasingly pronounced in the face of rapid urbanization, climate change, and growing anthropogenic pressures. In contemporary cities, the expansion of impervious surfaces has profoundly altered natural hydrological processes, intensifying stormwater runoff, increasing flood risks, and contributing to the degradation of water quality. At the same time, the increasing frequency and intensity of short-duration, high-magnitude rainfall events—largely associated with climate variability and climate change—have exposed the limitations of conventional drainage systems and underscored the urgent need for more resilient, integrated, and sustainable approaches to urban water management.

This book offers a timely and valuable contribution to the field by addressing urban stormwater management and rainwater harvesting not only from an engineering perspective, but also through the broader lenses of environmental sustainability, ecosystem-sensitive planning, and climate adaptation. The chapters presented in this volume provide a comprehensive examination of key issues such as the hydrological transformation of urban catchments, pollutant transport mechanisms in surface runoff, the first flush phenomenon, the environmental pressures exerted on receiving water bodies, and the role of sustainable urban drainage systems in mitigating these impacts. In addition, the book highlights the importance of rainwater harvesting as an alternative water resource and explores its applicability in large-scale structures, while also emphasizing its environmental and economic benefits through practical and analytical perspectives.

One of the major strengths of this volume lies in its interdisciplinary character. The issues surrounding urban runoff and stormwater quality are not confined to a single discipline; rather, they require the combined expertise of environmental engineering, civil engineering, urban and regional planning, landscape architecture, public policy, and sustainability studies. In this regard, the book successfully bridges theoretical knowledge and practical application,

offering insights that are equally relevant to researchers, graduate students, practitioners, municipal authorities, and policy makers.

In today's urban context, stormwater should no longer be regarded merely as a drainage problem to be conveyed away as quickly as possible. Instead, it must be understood as a resource to be managed, retained, treated, and reused within a circular and sustainable framework. This shift in perspective is essential for reducing pollutant loads, protecting receiving environments, improving water efficiency, and enhancing the resilience of cities against the increasing uncertainties of climate change.

It is my sincere belief that this book will serve as a significant academic reference and a practical guide for those engaged in the design, planning, and implementation of sustainable water management strategies. By encouraging readers to reconsider the role of stormwater in the urban environment, this work contributes meaningfully to the advancement of sustainable urban infrastructure and environmentally responsible water governance.

I would like to congratulate the author(s)/editor(s) for their valuable efforts in preparing this important volume, and I sincerely hope that it will prove beneficial to scholars, students, professionals, and decision-makers alike.

Editor: Prof Dr Raul DSG CAMPILHO

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CHAPTER 1

URBAN STORMWATER RUNOFF AND SURFACE-BORNE POLLUTION: ENVIRONMENTAL IMPACTS AND SUSTAINABLE MANAGEMENT STRATEGIES

Melike Büşra BAYRAMOĞLU KARŞI¹

Ercan BERBERLER²

Abstract

Rapid urbanization and climate change have substantially altered the natural hydrological cycle, increasing the conversion of rainfall into surface runoff and exacerbating both flood risks and water quality problems in urban areas. The expansion of impervious surfaces limits infiltration and natural retention processes, leading to the rapid conveyance of stormwater to receiving waters through drainage networks. This process accelerates the transport of suspended solids, heavy metals, nutrients, and hydrocarbons accumulated on urban surfaces, thereby intensifying pressures on aquatic ecosystems. In particular, the first flush phenomenon observed during the initial stages of rainfall events demonstrates that pollutant loads are not temporally uniform and that short-duration storms can generate disproportionately high environmental impacts. This study provides an integrated assessment of the hydrological

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basis of urban stormwater generation, the environmental impacts of pollutants transported by surface runoff, and the implications of changing precipitation regimes under climate change for urban water management. The limitations of conventional drainage approaches are critically discussed, and the role of sustainable urban drainage systems, low impact development practices, and nature-based solutions in mitigating urban flood risk and improving stormwater quality is evaluated. In this context, the study emphasizes that urban stormwater management should not be confined to hydraulics-oriented capacity expansion, but rather addressed within an ecosystem-based and climate-resilient integrated management framework.

Keywords: Urban stormwater, surface runoff, first flush, climate change

1. Introduction

The process of accelerating urbanization at the global scale has significantly altered the functioning of the natural hydrological cycle. In particular, the increase in impervious surfaces (asphalt, concrete, built-up areas) limits the retention of rainfall by soil and its infiltration into groundwater, markedly increasing surface runoff and peak flow rates (Fletcher et al., 2013). This situation leads to an increased flood risk in urban areas and to greater pollutant loads being conveyed to receiving water bodies (Marsalek & Schreier, 2009). Climate change is transforming urban stormwater management into a more complex and critical problem area. Global climate models indicate that, in many regions, the frequency and intensity of short-duration, high-intensity rainfall events will increase (Legg, 2021). The increase in extreme precipitation events challenges the hydraulic capacity of existing urban drainage infrastructures and results in surface runoff occurring at higher velocities and volumes (Zhang et al., 2021). This process not only elevates flood risk but also leads to more intense transport of pollutant loads carried by stormwater to receiving environments (Willems et al., 2012). In conventional approaches, stormwater was long considered a “relatively clean” flow component. However, the transport of pollutants accumulated on urban surfaces by surface runoff during rainfall has clearly demonstrated that stormwater constitutes a significant component of non-point source pollution fed by sources dispersed over wide areas rather than confined to a specific discharge point (Göbel et al., 2007). Traffic-related emissions, atmospheric deposition, tire and brake wear, metal releases from building materials, and particulate matter accumulated as a result of urban activities are transported to aquatic environments together with stormwater (Kayhanian et al., 2007). Therefore, stormwater is addressed not only as a hydraulic issue but also as a significant water quality and environmental risk component (Makepeace et

al., 1995). The pollutant-carrying characteristic of urban stormwater becomes even more pronounced through the “first flush” effect. During the initial stages of rainfall, pollutants that have accumulated on surfaces over extended periods are rapidly mobilized into runoff at high concentrations, causing sudden and intense pollutant loads in receiving environments (Lee et al., 2002). This situation creates serious ecological pressures, particularly for small water bodies and low-flow receiving environments (Paul & Meyer, 2001). In this context, urban stormwater is no longer addressed solely from the perspective of drainage and flood control but as an integrated environmental management issue. Sustainable urban drainage systems, low impact development approaches, and nature-based solutions form the foundation of a new paradigm aimed at managing stormwater in terms of both quantity and quality (Fletcher et al., 2015). These approaches offer significant opportunities not only for reducing surface runoff but also for retaining pollutant loads, enhancing infiltration, and strengthening urban ecosystem services (Ahiablame et al., 2012). The aim of this section is to evaluate, within a holistic framework, the hydrological basis of urban stormwater generation, the environmental impacts of pollutants transported by surface runoff, and the future significance of these processes in the context of climate change. In addition, by comparing conventional drainage approaches with sustainable stormwater management strategies, it is intended to provide scientific and practice-oriented implications for environmental engineering applications..

2. Urban Stormwater Generation and Hydrological Transformation

In the natural hydrological cycle, a significant portion of precipitation infiltrates into the soil, recharging groundwater reserves, while another portion is retained by vegetation and returned to the atmosphere through evaporation and transpiration (Dingman, 2015). These processes are among the fundamental mechanisms that limit the volume and velocity of surface runoff and maintain hydraulic balance within river basins (Chow & Maidment, 1988). In natural areas, the proportion of rainfall converted into surface runoff is generally limited, and a large part of precipitation reaches receiving environments with a delayed and attenuated hydrological response (Beven, 2012). With urbanization, impervious surfaces replacing natural land covers significantly reduce the infiltration capacity of rainfall, thereby markedly increasing the surface runoff rate (Arnold & Gibbons, 1996). The widespread presence of asphalt, concrete, and built-up areas directs precipitation rapidly into drainage systems, resulting in both a temporal acceleration of runoff response and an increase in peak discharges (Booth, 1997). This hydraulic transformation

observed in urban catchments causes responses to rainfall events to occur more abruptly and with higher flow rates (Walsh et al., 2005). An increase in the proportion of impervious surfaces affects not only the quantity of surface runoff but also its spatial distribution and the degree of hydraulic connectivity (Brabec et al., 2002). Urban drainage networks artificially connect natural flow paths, enabling stormwater to reach receiving environments within a short time (Shuster et al., 2005). This condition shortens water residence time at the catchment scale and prevents attenuation of the hydrological response, thereby increasing flood risk (Hamel et al., 2013). In the quantitative assessment of urban hydrological transformation, the runoff coefficient is a commonly used parameter for comparing the hydraulic response of different surface types to precipitation (Chow & Maidment, 1988). While the runoff coefficient generally exhibits low values in natural soils and green areas, it can increase up to the range of 0.7–0.95 for impervious surfaces such as asphalt and concrete (Viessman, 1989). This surface-dependent difference causes even small-scale rainfall events to generate significant amounts of surface runoff in urban areas (Butler, 2014). The effects of different land use types on hydrological behavior are of critical importance in determining urban planning and stormwater management strategies (Fletcher et al., 2013). Residential areas, commercial zones, and transportation infrastructures produce different hydraulic responses in terms of impervious surface ratios and drainage connectivity (Jacobson, 2011). This heterogeneous structure complicates the application of uniform solutions for stormwater management in urban catchments and highlights the necessity of site-specific approaches (Shuster et al., 2014). Urban hydrological transformation, beyond the quantitative increase in surface runoff, leads to the conveyance of water to receiving environments without passing through natural filtration and retention processes (Paul & Meyer, 2001). This condition increases the pollutant transport potential of stormwater and demonstrates that water quality problems in urban catchments are directly related to hydraulic transformation (Walsh et al., 2005). Therefore, urban stormwater management should be addressed not only through engineering solutions aimed at increasing hydraulic capacity, but also through holistic approaches that seek to restore natural hydrological processes at the urban scale (Fletcher et al., 2015).

3. First Flush Effect and Pollutant Accumulation

The first flush effect is a frequently addressed phenomenon in urban stormwater research and refers to the condition in which pollutant concentrations transported by surface runoff at the beginning of a rainfall event are higher than those observed in the later stages of the event (Lee et al., 2002; Mamun et al., 2020). This phenomenon is associated with the rapid mobilization of pollutants

accumulated on urban surfaces during antecedent dry periods, and early-stage runoff may result in the conveyance of a substantial portion of the total pollutant load to receiving environments within a relatively short time (Deletic, 1998). In the literature, it is emphasized that threshold-based approaches, which assume that a certain fraction of the total pollutant load is transported during the early stages of the rainfall volume, have been used to quantitatively describe the first flush phenomenon; however, these approaches are not universal and yield variable results under different catchment conditions (Maniquiz-Redillas et al., 2022). One of the commonly used methods to evaluate the presence of the first flush effect is the examination of the relationship between cumulative runoff volume and cumulative pollutant load throughout a rainfall event. This approach demonstrates that pollutant transport is not temporally homogeneous and that runoff occurring during the early stages of rainfall may have a disproportionate impact on water quality (Deletic, 1998). Therefore, the first flush phenomenon is evaluated not only as a hydrological process but also as a critical design parameter for the placement and sizing of urban stormwater treatment systems (Maniquiz-Redillas et al., 2022). Studies indicate that the intensity of the first flush effect varies depending on both the morphological characteristics of the urban catchment and rainfall characteristics. In small-scale catchments that are more homogeneous in terms of surface properties, the concentration of pollutant accumulation within more confined areas may lead to a pronounced first flush behavior at the onset of rainfall (Mamun et al., 2020). In contrast, in large and heterogeneous catchments, the spatial dispersion of pollutant sources has been reported to result in a weaker or more irregular first flush effect (Mamun et al., 2020). Meteorological variables such as rainfall intensity, rainfall duration, and the length of the antecedent dry period directly influence the mobilization potential of pollutants accumulated on surfaces, thereby determining the extent to which first flush behavior occurs (Maniquiz-Redillas et al., 2022). The characteristics of first flush behavior may also vary depending on pollutant type. Total suspended solids (TSS) and particle-bound organic pollutants generally exhibit higher concentrations at the beginning of rainfall events, whereas the transport of certain dissolved-phase pollutants may be more evenly distributed over the duration of the rainfall (Lee et al., 2002). This difference arises from interactions between the modes of pollutant accumulation on urban surfaces and the transport mechanisms occurring during stormwater runoff. In this context, first flush analyses provide an important analytical tool not only for event-based water quality assessments but also for the development of seasonal and long-term urban stormwater management strategies (Lee et al., 2002; Lee et al., 2004). Recent studies indicate that the first flush phenomenon should not be considered a static behavior valid

under all conditions; rather, it is a dynamic process sensitive to rainfall and catchment characteristics (Gao et al., 2023). Newly developed approaches within this scope aim to define the quantitative boundaries of the first flush effect more reliably through statistical simulation techniques and to improve the performance of stormwater management practices (Perera et al., 2021).

4. Pollutants Transported from Urban Surfaces

Urban stormwater conveys a wide variety of pollutants to receiving environments depending on different land use types and surface characteristics (Göbel et al., 2007). These pollutants primarily accumulate on road surfaces, rooftops, parking lots, and industrial areas as a result of dry deposition, traffic emissions, and urban activities, and are mobilized by surface runoff during rainfall events (Kayhanian et al., 2012). The magnitude of pollutant loads accumulated on surfaces is significantly influenced by factors such as the length of the antecedent dry period, traffic density, and land use type (Maharjan et al., 2017). Total suspended solids (TSS) are among the most commonly reported pollutant fractions in urban stormwater and constitute the primary carrier phase to which many pollutants transported by surface runoff are attached (Sansalone & Buchberger, 1997). It has been shown that TSS concentrations reach high values particularly in runoff originating from roads with heavy traffic loads, and that these particles provide an important adsorption surface for heavy metals and hydrophobic organic compounds (Kayhanian et al., 2012). Therefore, TSS should be evaluated both as a physical pollutant and as a determining medium in the transport of secondary pollutants (Zgheib et al., 2012). Heavy metals are among the toxic pollutants frequently detected in urban surface runoff, with elements such as zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd) being particularly prominent (Göbel et al., 2007). A significant portion of these metals accumulates on surfaces as a result of tire and brake wear, vehicle exhaust emissions, and the degradation of building materials under atmospheric conditions (Kayhanian et al., 2012). During rainfall events, the wash-off of metal-containing particles from surfaces may lead to toxic effects on sediment quality and benthic organisms in receiving water bodies (Zgheib et al., 2012). Nitrogen (N) and phosphorus (P) compounds, which are nutrients, constitute major pollutant groups transported by urban stormwater and contribute to increased eutrophication risk (Hathaway & Hunt, 2011). A substantial portion of these compounds originates from fertilizers used in urban green areas, accumulated organic wastes, and atmospheric deposition (Maharjan et al., 2017). Dissolved and particle-bound nutrients transported by stormwater may cause ecological problems such as algal blooms and decreases in dissolved oxygen, particularly in small and low-flow receiving

environments (Ding et al., 2015). Oil and grease fractions and hydrocarbons can reach significant concentrations in surface runoff originating from areas with intensive traffic and industrial activities (Zgheib et al., 2012). Engine oils, fuel leaks, and organic compounds dissolved from asphalt surfaces mix with stormwater and may cause toxicity and aesthetic problems in receiving environments (Kayhanian et al., 2012). Due to their hydrophobic properties, these compounds have the potential to bind to sediments and create long-term environmental risks (Maharjan et al., 2017). The impacts of pollutants transported by urban stormwater on receiving environments vary depending on the hydrodynamic characteristics of the water body and ecosystem sensitivity (Göbel et al., 2007). Small streams and lakes are more sensitive to sudden pollutant loads and may exhibit rapid water quality deterioration and signs of biological stress (Paul & Meyer, 2001). Stormwater directed into sewer systems may, in combined systems, lead to the direct discharge of untreated pollutants into receiving environments through combined sewer overflows (Maharjan et al., 2017). Therefore, urban surface runoff poses multidimensional environmental risks for both surface waters and urban infrastructure systems (Hamel et al., 2013).

5. Urban Stormwater Management Approaches

Conventional urban drainage systems are based on an engineering approach that aims to remove stormwater from urban surfaces as quickly as possible and convey it to sewer networks and receiving environments (Butler & Davies, 2011). Although this approach provides practical solutions for flood control, particularly during rapid urbanization processes, it leads to increased surface runoff volumes and the transport of pollutants to receiving environments without undergoing any treatment or retention process (Fletcher et al., 2013). Moreover, the hydraulic capacity limits of existing drainage infrastructures may result in system surcharges during extreme rainfall events and combined sewer overflows in combined sewer systems (Willems & Olsson, 2012). Sustainable Urban Drainage Systems (SUDS) and Low Impact Development (LID) approaches aim not only to remove stormwater but also to retain it at its source and manage it in a manner more closely aligned with natural hydrological processes (Fletcher et al., 2015). Practices developed within this framework offer an integrated approach that seeks to reduce surface runoff volumes, attenuate peak discharges, and control pollutant loads transported by stormwater (Ahiablame et al., 2012). Considered within the scope of nature-based solutions, these systems contribute to the partial restoration of the disrupted urban water cycle. Permeable pavements are among the structural solutions that allow stormwater to infiltrate into underlying layers

by percolating through the surface and are widely applied particularly in parking areas and low-traffic road surfaces (Sansalone & Teng, 2004). Such applications not only reduce surface runoff volumes but also contribute to the retention of particle-bound pollutants, thereby decreasing the pollutant load reaching receiving environments (Bean et al., 2007). The long-term performance of permeable pavements may vary depending on underdrain design and maintenance conditions (Sansalone & Teng, 2004). Rain gardens and biofiltration systems are practices designed to promote the retention, infiltration, and treatment of stormwater through biophysical processes using vegetative cover and permeable filter media (Hunt et al., 2006). It has been reported that a significant portion of total suspended solids, heavy metals, and nutrients can be retained in these systems, thereby reducing both the volume and pollution potential of surface runoff (Blecken et al., 2012). Microbial processes occurring in the plant root zone play a determining role particularly in the removal of nitrogen compounds (Nazarpour et al., 2023). Green infrastructure applications aim to manage stormwater in a distributed manner at the urban scale through green roofs, urban green spaces, and bioretention systems (Berndtsson, 2010). Green roofs temporarily store a significant portion of rainfall, thereby reducing surface runoff volumes and peak discharges and alleviating the burden on urban drainage systems (Mentens et al., 2006). In addition, green infrastructure solutions provide multiple environmental co-benefits, such as mitigating the urban heat island effect and enhancing ecosystem services (Berndtsson, 2010). One of the significant advantages of SUDS and LID practices is that they offer more flexible and modular solutions compared to centralized infrastructure investments (Ahiablame et al., 2012). However, the performance of these systems is highly dependent on local climatic conditions, soil properties, and maintenance levels, and the expected hydraulic and environmental benefits may not be achieved in cases of improper design or insufficient maintenance (Nödler et al., 2012). Particularly in densely built urban areas, land use pressure emerges as a significant limiting factor for the widespread implementation of such practices (Fletcher et al., 2015). Developing effective and sustainable solutions in urban stormwater management requires that conventional drainage infrastructures and SUDS/LID practices be addressed within a holistic framework as complementary rather than mutually exclusive approaches (Willems & Olsson, 2012). Integrated stormwater management strategies planned at the catchment scale enable the simultaneous consideration of flood risk reduction and water quality objectives (Fletcher et al., 2013). In this context, structuring engineering solutions in alignment with local government policies and spatial planning processes is

of critical importance for the long-term success of urban water management. sahiptir.

6. Climate Change Perspective

Climate change has become one of the principal environmental pressures directly affecting urban stormwater management by altering the temporal and spatial distribution of hydrometeorological processes (Willems et al., 2013). Increases in atmospheric temperatures enable the air to retain more water vapor, thereby increasing the likelihood of short-duration, high-intensity rainfall events (Fowler et al., 2021). Global and regional climate projections indicate statistically significant increases in the frequency and intensity of extreme precipitation in many mid-latitude cities (Cea et al., 2022). This trend markedly increases surface runoff volumes and peak discharges in urban areas (Arnbjerg-Nielsen et al., 2013). In cities with high proportions of impervious surfaces, increases in rainfall intensity lead to the exceedance of drainage system design capacities and to more frequent flood events (Willems et al., 2013). The resulting hydraulic pressure is not limited to flood risk but also causes pollutant loads transported by stormwater to reach receiving environments suddenly and intensively (Cea et al., 2022). Changes in precipitation regimes associated with climate change also affect the wash-off dynamics of pollutants accumulated on urban surfaces (Kumar et al., 2022). High-intensity rainfall occurring after prolonged dry periods may result in the rapid mobilization of accumulated pollutants and make the “first flush” effect more pronounced (Bertrand-Krajewski et al., 1998). This process increases the transport of heavy metals, total suspended solids, and hydrocarbon fractions to receiving environments, thereby imposing additional pressure on aquatic ecosystems (Xiao et al., 2017). A large proportion of existing urban stormwater infrastructures has been dimensioned based on design rainfall derived from past climatic conditions and may be structurally inadequate to cope with projected future extreme precipitation regimes (Willems et al., 2013). This situation highlights the sensitivity of urban infrastructure to climate change and necessitates the updating of engineering design criteria (Fowler et al., 2021). Climate change adaptation-based stormwater management approaches focus not only on increasing hydraulic capacity but also on promoting solutions that reduce surface runoff at its source (Arnbjerg-Nielsen et al., 2013). Sustainable urban drainage systems and low impact development practices enhance the resilience of urban areas to the adverse effects of climate change by retaining, delaying, and increasing the infiltration of stormwater (Kumar et al., 2022). Such nature-based solutions contribute not only to reducing flood risk but also to protecting water quality by limiting the transport of pollutant loads carried

by stormwater to receiving environments (Xiao et al., 2017). In the context of climate change, the effectiveness of urban stormwater management is closely related not only to engineering solutions but also to holistic planning and policy instruments (Willems et al., 2013). Long-term adaptation strategies require the integration of land use planning at the city scale, the widespread implementation of green infrastructure, and the incorporation of climate-sensitive design principles into infrastructure projects (Arnbjerg-Nielsen et al., 2013). This approach necessitates the adoption of a proactive rather than solely reactive framework in managing the impacts of climate change on the urban water cycle (Fowler et al., 2021).

7. Conclusion and Future Perspective

In urban areas, stormwater management has evolved into a complex field of environmental management that cannot be reduced solely to increasing drainage capacity due to expanding impervious surfaces and changing precipitation regimes (Willems et al., 2013). The increase in surface runoff volume amplifies pollutant loads transported to receiving environments and exerts persistent pressure on water quality (Göbel et al., 2007). Therefore, urban stormwater should be evaluated within an integrated urban water management framework in which flood control and water quality management are addressed simultaneously (Fletcher et al., 2015). Sustainable urban drainage systems and low impact development approaches have the potential to limit both hydraulic loads and pollutant transport by reducing surface runoff at its source (Ahiablame et al., 2012). Nature-based solutions assume a complementary role to conventional gray infrastructure solutions by providing multiple ecosystem services, such as increasing infiltration, retaining pollutants, and improving the urban microclimate (Fletcher et al., 2015). The widespread implementation of these approaches is regarded as a structural transformation tool that strengthens cities' adaptive capacity to climate change (Arnbjerg-Nielsen et al., 2013).

The integration of stormwater management into land use, green infrastructure planning, and urban design decisions within local government policy and planning processes is of critical importance for long-term effectiveness (Willems et al., 2013). Planning at the catchment scale contributes to reducing hydraulic and pollutant load imbalances among different urban sub-catchments, thereby providing a more equitable and effective management framework (Fletcher et al., 2015). Furthermore, the institutionalization of maintenance, monitoring, and performance evaluation mechanisms is decisive for ensuring that implemented systems maintain their functionality over time (Ahiablame et al., 2012). From a future perspective, research needs related to urban stormwater management

become even more pronounced in the context of uncertainty in extreme precipitation under climate change and the temporal variability of pollutant loads (Fowler et al., 2021). The limited availability of long-term monitoring data increases uncertainties in modeling studies and may constrain the reliability of design criteria (Willems et al., 2013). Therefore, it is necessary to promote multidisciplinary research that jointly addresses hydrology, water quality, ecology, and urban planning components (Arnbjerg-Nielsen et al., 2013). In conclusion, under conditions of climate change and rapid urbanization, urban stormwater management should be addressed not only as an engineering-oriented technical field but also as a holistic sustainability issue encompassing governance, planning, and environmental policy dimensions (Fletcher et al., 2015). The adoption of an integrated urban water management approach will enhance cities' resilience to floods while providing long-term and lasting benefits for the protection of receiving water bodies (Willems et al., 2012).

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CHAPTER 2

ZONGULDAK PROVINCE DEMIR PARK SHOPPING CENTER RAINWATER HARVESTING ACCOUNT

Berna AKSOY¹

ABSTRACT

This study examines the importance of rainwater harvesting as a hydrological variable, its potential as an alternative to existing water sources, its storage function against drought, and an analysis of the benefits and drawbacks of rainwater.

Within the scope of the study, the applicability of rainwater harvesting systems was evaluated, and collection methods and management processes were examined. In addition, the development of collection systems established from the past to the present was examined, collection and storage methods were determined, and the areas of use of rainwater were identified. Considering the increasing need for water today, the integration of rainwater into daily life is of great importance.

In this context, the potential amount of rainwater that can be collected from the roof of the Demirpark Shopping Center, located in Zonguldak province and covering an area of approximately 13,800 m², has been calculated. According to the findings, it has been determined that a rainwater harvesting system

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implemented on the roofs of Demirpark Shopping Center could collect a significant amount of water annually and contribute to reducing urban water consumption.

In conclusion, it has been demonstrated that rainwater harvesting is an important method for sustainable water management, can contribute to the conservation of water resources, and that further studies in this area are necessary.

Keywords: Rainwater Harvesting, Water Management, Sustainability, Demirpark Shopping Mall, Zonguldak, Climate Analysis.

INTRODUCTION

Although water is an indispensable resource for the continuity of life, it is under increasing pressure worldwide. Factors such as rapid population growth, urbanization, industrialization, and climate change threaten the sustainability of existing water resources and have made the sustainable management of water resources one of the most important environmental issues of our time.

According to United Nations (UN) estimates, the world population is expected to reach 9.7 billion by 2050, and this increase is projected to lead to a significant rise in water demand.

The sixfold increase in global water consumption over the past 100 years (Wada et al., 2016) and the projected annual increase of 1% in the future highlight the seriousness of the situation (WWAP, 2018). In particular, the increasing demand for water in urban areas has led to the inadequacy of existing water resources and the need to explore alternative water sources.

When assessing the situation in Turkey specifically, it is observed that the amount of available water per capita is 1,500-1,600 m³/year and that the country is at risk of water scarcity. It is expected that Turkey's population will reach 87 million in the next 20 years and that the amount of water per capita will drop to 1,042 m³/year (Eren et al., 2016). This situation highlights the risk of Turkey entering the category of water-scarce countries.

In this context, the search for alternative water sources for the sustainable management of natural resources has become a topic of great importance in many countries in recent years (Asano and Levine, 1996; Sturm et al., 2009; Zhang et al., 2010; Eren et al., 2016).

Within the scope of sustainable water resource management, rainwater harvesting (RWH) stands out as one of the most natural, economical, and environmentally friendly methods among these alternative sources. These

systems are becoming increasingly important because the collection, storage, and reuse of rainwater contribute to reducing tap water consumption and more efficient use of water resources. Additionally, these systems play an effective role in meeting domestic, industrial, agricultural, and environmental water demands (Aladenola and Adeboye, 2009; Worm and Hattum, 2006). Especially in large-scale commercial buildings, the implementation of RWH systems offers multiple benefits, including economic and environmental advantages, such as meeting the increasing water demand in urban areas, replenishing groundwater resources, and reducing flood risks. This method is gaining attention for its applicability at both individual and societal scales and is becoming increasingly widespread worldwide. For example, in Germany, RWH systems, particularly the use of rainwater in toilets and garden irrigation, have reduced municipal water consumption by 30-50% (Herrmann and Schmida, 1999). Similarly, in large cities such as São Paulo, Brazil, RWH systems are being used effectively to alleviate water scarcity issues (Campisano et al., 2017).

Significant steps are also being taken in Turkey in the field of RWH. Various projects are being implemented to promote rainwater collection systems, particularly in large cities such as Istanbul, Ankara, and Izmir. For example, the Istanbul Metropolitan Municipality aims to collect rainwater and use it to irrigate parks and gardens as part of its “Rainwater Management Project” launched in 2020. Additionally, the “National Water Plan” published by the Ministry of Agriculture and Forestry in 2021 identifies the widespread adoption of RWH as an important goal.

RWH systems are regulated by standards such as DIN1989 (Germany), Turkey (Official Gazette of the Republic of Turkey, 2017; Official Gazette of the Republic of Turkey, 2021), and BS8515 (United Kingdom). In addition, there are national and international companies that install, assemble, and operate these systems.

In this study, the RWH potential of the DEMİR PARK Shopping Center in Zonguldak province was examined. The rainwater potential was calculated by considering current material and labor costs, tap water prices, and different storage, rainfall, and area scenarios. The uses of collected rainwater for cleaning, toilets, flushing, irrigation, and drinking water after treatment were analyzed. In addition, the effectiveness of the system was evaluated by taking into account the irrigable green areas around the shopping center.

RAINWATER HARVESTING (RWH)

Definition of RWH

RWH is the collection of rainwater using various methods and systems. This method is one of the important alternative sources of sustainable water management.

With this method, rainwater is collected from roofs, surfaces, or natural areas, filtered, and stored in tanks or underground cisterns. The collected water can be used in agriculture, garden irrigation, cleaning, and even as drinking water after being properly treated (Figure 1).

RWH systems offer a sustainable solution to water scarcity. They also help replenish groundwater and mitigate the effects of drought.

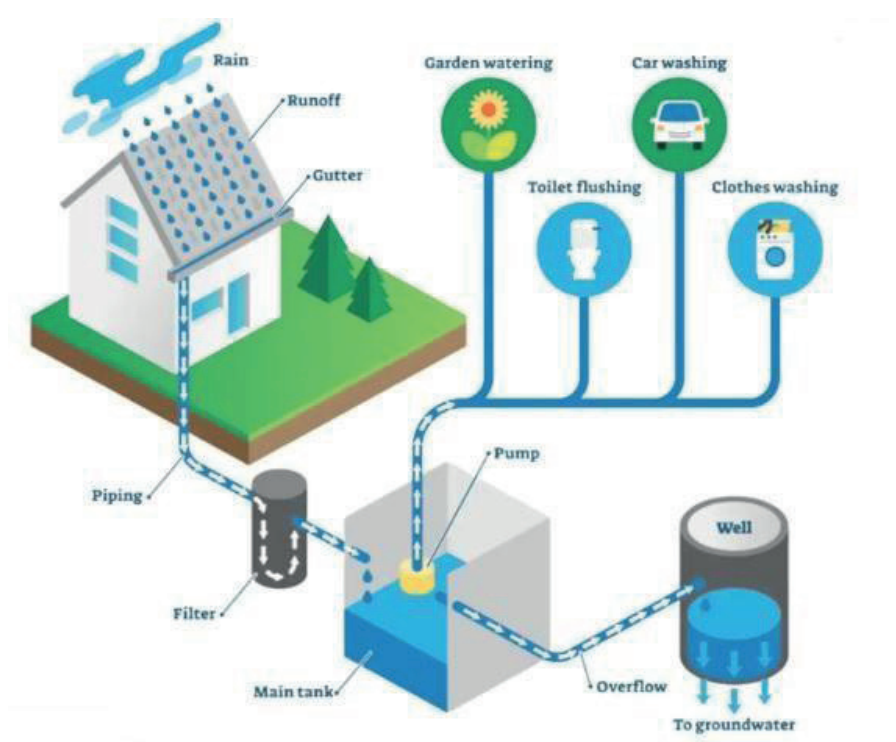


Figure 1. RWH and Water Utilization Systems

MATERIALS AND METHODS

Definition of the Study Area

Zonguldak Province, located in the Black Sea Region, has a climate that combines characteristics of both continental and maritime climates. Rainfall is high throughout the year in the region, with snowfall also occurring during the winter months (General Directorate of Meteorology, 2024). The Demirpark Shopping and Lifestyle Center, located in the center of Zonguldak, serves as a suitable example for investigating the potential use of rainwater that can be collected through RWH methods. Demirpark Shopping Center has a total enclosed area of approximately 13,800 m² (Figures 2, 3, 4). The shopping center has 25 stores, food and beverage areas, and entertainment units. It also has a parking lot and landscaped green areas around it. In this study, the potential for using rainwater collected on the roof of Demirpark Shopping Mall as gray water and flush water in toilets, for watering green areas outside the building, and for cleaning purposes was evaluated. Considering the average annual rainfall in the region and the total collectable surface area of the roof, which is 13,800 m², sustainable water management strategies were developed.



Figure 2. DemirPark Shopping Center (Zonguldak 2023)

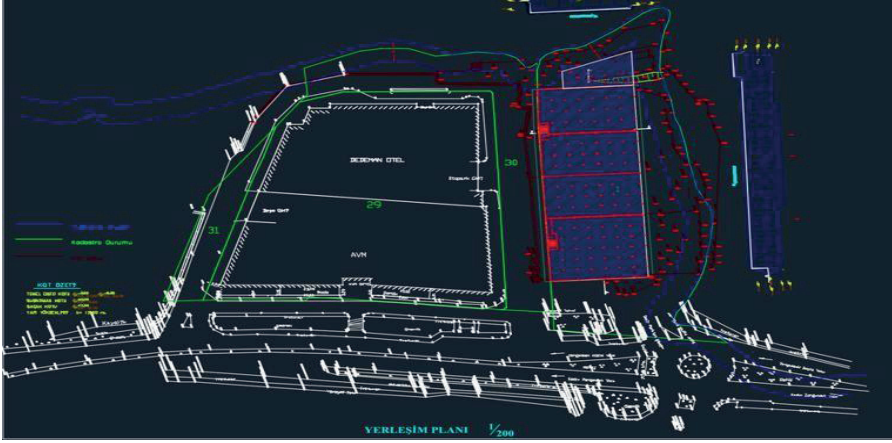


Figure 2. Layout plan of Demir Park Shopping Center



Figure 4. Basement floor plan of Demir Park Shopping Center (Approximate area 13,800 m²)

In the calculations, measurements of the roof area of the shopping center building and the surrounding green areas were obtained from the Zonguldak Municipality. The “Rainwater Yield (YSV)” equation defined in accordance with the German DIN 1989 standard was used to calculate the amount of rainwater that could accumulate on the roof of the shopping center.

$$YSV (m^3) = A \times P \times \zeta K \times FK \quad (1)$$

In this equation, A (m^2) represents the roof area of the building; P (mm) represents the total annual rainfall; ζ_k represents the roof efficiency coefficient specified in DIN 1989 (0.8); and F_k represents the filter efficiency coefficient defined in the same standard (0.9).

According to long-term precipitation data (1939–2024) obtained from the General Directorate of Meteorology (MGM), the annual average precipitation amount for Zonguldak Province has been determined as 1226.4 mm (Table 1). Additionally, the monthly calculated total rainwater yield (YSV) values are provided in Table 2.

Table 1. Climate Characteristics of Zonguldak between 1939 and 2024 (MGM, 2024)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Ave. Temperature (°C)	6.3	6.4	7.6	11.3	15.4	19.7	21.9	22.0	19.0	15.4	11.9	8.5	13.8
Ave. Max. Temperature (°C)	9.4	9.8	11.4	15.4	20.2	24.6	27.0	27.0	24.1	20.0	15.8	11.9	18.3
Ave. Min. Temperature (°C)	3.6	3.6	4.8	7.2	11.2	15.1	17.8	18.3	15.3	11.3	7.9	5.0	9.4
Ave. Sunshine Duration (hours)	2.3	3.2	4.3	5.9	8.0	9.7	10.8	9.7	7.2	4.9	3.0	2.0	5.9
Ave. Number of Rainy Days	18.07	15.47	13.52	11.27	9.83	8.10	5.87	6.55	8.27	11.32	13.29	16.29	137.8
Ave. Monthly Total Precipitation (mm)	139.7	98.7	82.0	64.9	57.4	74.4	60.8	80.8	102.9	146.8	154.0	140.1	1226.4
Highest Temperature (°C)	24.1	26.7	31.7	33.6	36.7	40.5	39.5	39.8	35.9	30.8	28.1	40.5	
Lowest Temperature (°C)	-8.7	-8.0	-6.4	-2.1	3.8	8.0	11.2	10.9	5.9	-3.2	-7.4	-8.0	

Table 2. Rainfall values and rainwater yields for Zonguldak province between 1939 and 2024

Month	Average Number of Rainy Days	Average Monthly Total Precipitation (mm)	Monthly Rainwater Yield (RWY) (DIN 1989) m ³
January	18.07	139.7	1388.06
February	15.74	98.8	981.68
March	15.3	98.2	975.72
April	12.1	64.9	644.85
May	10.87	54.7	543.50
June	8.7	74.4	739.24
July	6.64	69.3	688.56
August	6.8	80.9	803.56
September	8.45	102.8	1022.82
October	12.29	146.8	1458.60
November	13.76	141.9	1409.92
December	17.43	154.0	1530.14
Annual	146.2	1226.4	12185.65

METHODS

In this study, four different scenarios were developed to assess the RWH potential from the roof of Demirpark Shopping Mall. In Scenario 1, based on the annual total rainfall data of 1226.4 mm, it was determined that approximately 12,185 m³ of rainwater could be collected annually according to the DIN 1989 standard. Scenario 2 was evaluated based solely on the rainfall amount (447 mm) during the irrigation season (April–September), resulting in an annual yield of 4,441 m³. In Scenario 3, based on European standards, it was assumed that only 5% of the annual rainfall could be utilized, yielding 609 m³ of rainwater. Finally, Scenario 4 was conducted for May, the month with the highest rainfall; it was calculated that with 154 mm of rainfall in this month, the annual yield could be 1,530 m³ (Table 3). These scenarios demonstrate how the RWH system can vary depending on different climatic and usage conditions and provide an important foundation for ensuring flexibility in system design.

Table 3. Possible rainwater yield (YSV) scenarios and potential storage volumes

	Scenario 1: According to annual total rainfall	Scenario 2: According to irrigation season (April - September total rainfall)	Scenario 3: According to European standard 5% of annual total rainfall	Scenario 4: According to maximum monthly rainfall (December)
Annual total rainfall (mm)	1226.4	447	61.32	154.00
Shopping mall roof area (m ²)	13800	13800	13800	13800
Annual rainwater yield (RWY) (DIN 1989) (m ³)	12185.51	4441.39	609.28	1530.14

RESULTS and DISCUSSION

Rainfall Analysis Results

Four different scenarios created for the design of the RWH system were analyzed to comparatively evaluate the annual rainwater yield that could be collected from the roof of Demir Park Shopping Mall. Scenario 1 was calculated based on the annual total rainfall of 1,226.4 mm and demonstrated the highest annual yield, revealing a potential of approximately 12,185 m³ of water. This scenario theoretically offers the highest water savings; however, the assumption that all rainfall can be effectively collected is not always feasible in real-life conditions.

Scenario 2, on the other hand, is based solely on rainfall data from the irrigation season (April– September) and offers a more realistic approach with an annual water yield of approximately 4,441 m³, which is suitable for seasonal needs. Therefore, this scenario stands out as the basis for designing the system to meet outdoor irrigation and cleaning needs, especially during the summer months.

Scenario 3 assumes that only 5% of the total annual rainfall can be used according to European standards and offers a water yield of 609 m³, thus proposing a rather conservative and low-capacity system. It is safe but falls far short of the real potential.

Scenario 4, on the other hand, was calculated based on the monthly maximum rainfall in the region during December and provided a water yield of 1,530 m³ (Table 4). This scenario is important for understanding how the system will perform during periods of excessive rainfall and is valuable as a reference for determining system capacity limits.

Table 4. Annual Yield and Evaluation According to Different Scenarios for RWH

Scenario No	Description	Total Annual Rainwater Yield (m ³)	Advantage	Disadvantage
1	According to annual total rainfall	12,185.51 m ³	Highest yield, covers the whole year	Too optimistic, collecting all rainfall may not always be possible
2	Only irrigation season (April–September)	4,441.39 m ³	Suitable for seasonal needs	Yield decreases, excludes other months
3	European standard: 5% of annual rainfall	609.28 m ³	Very conservative and safe	Does not reflect actual potential
4	Wettest month (December)	1,530.14 m ³	Can be designed for extreme rainfall periods	Not distributed across the whole year

Since the storage volumes that may be formed according to the calculated Rainwater yields (RY) are high, it is considered more reasonable and logical to choose scenario 4 (DECEMBER) when considering the selection of the most appropriate storage volume and, consequently, storage costs as one of the largest costs in the system. This situation is generally taken into account in studies and application projects. At this point, it would be a more accurate decision to use the calculated rainwater yield (1,530 m³) based on the maximum monthly rainfall total for December (154 mm) for the storage volume, considering the water consumption in the building. Ultimately, it is considered that the calculated rainwater yield for December can be used as the optimal storage volume (Figure 5).

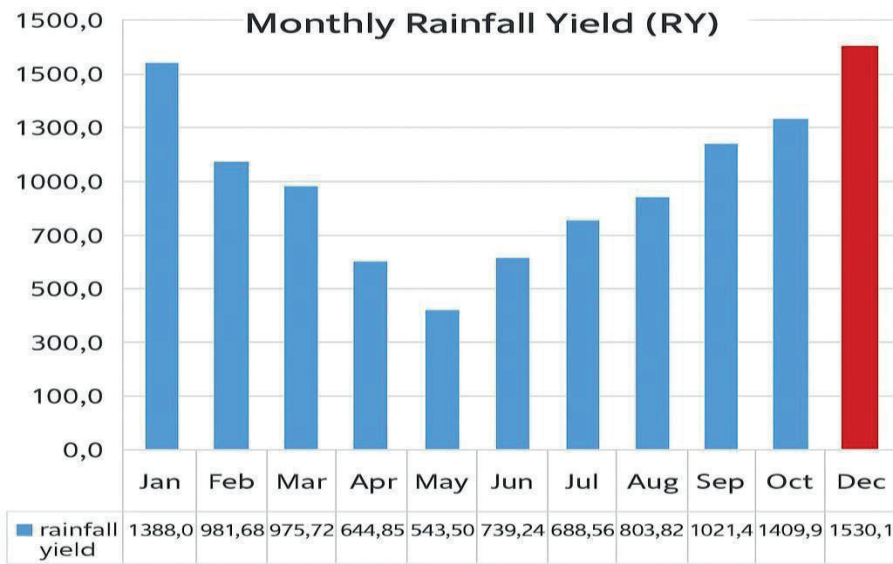


Figure 5. Monthly total rainfall yields (RY) (m³) by month

Storage System

The location and placement of storage tanks is also important. It is preferable for storage tanks to be buried underground and protected from external environmental conditions (temperature, freezing, material life, and vandalism). The storage capacity was selected based on the maximum total rainfall for December, and it is generally considered that the storage capacity will be sufficient as rainfall will be below this capacity in other months. If the water in the storage runs out, it will be necessary to obtain water from the mains supply.

Economic Analysis

In determining the water requirements of green areas, 5 liters/m² was used for each irrigation. The amount of water required for shopping center cleaning was determined in consultation with the shopping center management and was set at approximately 2000 liters (2 m³) for each cleaning. The water requirement for irrigating green areas was calculated as 1,800 m² of green area per irrigation, 1,800 m² x 5 liters/m² = 9,000 liters = 9 m³. The shopping center management stated that cleaning is performed twice a week, and the water quantities consumed are specified in Table 5.

Table 5. Annual water requirements for green areas and building cleaning

Roof rainwater yield and selected storage volume (m ³) for December	1530,14
Water requirements for green areas in each irrigation cycle (m ³)	9
Annual water requirement for cleaning twice a week (m ³)	208 (52 week *2*2)
Annual water requirement for watering once a week (m ³)	468 (52 week *9)
Total annual water requirement of the building (m ³)	676

Water accumulation and consumption rates vary depending on the rainfall pattern in the Zonguldak region. There is a significant decrease in rainfall, especially in May, June, July, and August. During these months, the amount of rainwater that the roof can provide was measured as 543.50 m³, 739.26 m³,

688.56 m³, and 520.82 m³, respectively. During the same period, the need to water the shopping center's green areas also increases as temperatures rise. Therefore, water demand in the building is higher during these months, and the stored rainwater is depleted more quickly due to the decrease in rainfall.

The total amount of rainwater that can be collected from the Demir Park Shopping Center roof throughout the year is calculated to be 12,185.51 m³. This amount easily meets the annual need of 676 m³ of water for cleaning and irrigation. In fact, the 1,530.14 m³ of rainwater that can be obtained in December alone is sufficient to meet the annual water demand. When appropriate filtration and treatment systems are used, the collected rainwater can be used as gray water or even as drinking water.

CONCLUSIONS AND SUGGESTIONS

Conclusions

Within the scope of this study, the role of RWH in sustainable water management has been evaluated in light of today's important environmental problems such as population growth, urbanization, climate change, and limited water resources. The importance of rainwater as an alternative water source has been addressed both theoretically and practically; its historical development, advantages, disadvantages, collection methods, and areas of application have been examined in detail. The study has demonstrated how RWH can provide an effective solution, particularly in regions experiencing drought and water stress.

In the study, the RWH system was practically evaluated using the example of Demir Park Shopping Center, located in a region with relatively high rainfall, such as Zonguldak province. Based on calculations made for the approximately 13,800 m² roof area, the annual average rainfall and the water potential that the system could provide were determined using the DIN 1989 standard as a basis. Considering an annual average rainfall of 1,226.4 mm, it was calculated that approximately 12,185 m³ of rainwater could be collected annually. This value indicates that a significant amount of water could be reused and that water consumption from the network could be reduced.

Analyses conducted under different scenarios, particularly Scenario 4 (maximum monthly rainfall – December), show that the water yield of 1,530.14 m³ obtained under this scenario demonstrates that the system can operate effectively even during critical periods throughout the year.

The total annual water requirement for the shopping mall's weekly cleaning activities and green area irrigation needs has been calculated as 676 m³. This amount can be met even with the rainwater that can be collected in December. Additionally, considering that rainfall decreases between May and August, it has been observed that water demand increases during these periods, but rainwater yield decreases. This situation necessitates the proper planning of the storage system's volume and the creation of sufficient reserves for use during dry periods.

This study has shown that RWH not only saves water, but also reduces flood risk by reducing surface runoff, reduces pressure on infrastructure, and replenishes groundwater resources. From an economic perspective, it has been observed that installation costs yield a return on investment in the medium term, with the system able to amortize itself within 2 to 5 years. This makes the system attractive for both individual and institutional users.

In conclusion, RWH systems are a multifaceted application that supports environmental sustainability and provides economic benefits. The widespread adoption of these systems, particularly in areas such as public buildings, shopping centers, and industrial facilities with large roof areas, is of strategic importance for water management.

Suggestions

- The installation of RWH systems should be encouraged in buildings with large surface areas, such as the roof of Demir Park Shopping Mall.

- During implementation, hygiene measures such as filtration systems and first flush discharge mechanisms should be taken into consideration.
- Regular analyses of collected rainwater should be conducted to monitor its quality for use.
- Local authorities should implement regulations requiring the installation of RWH systems in building permits.
- Periodic inspection mechanisms should be established for the maintenance and control processes of the systems.
- Awareness-raising campaigns should be organized in educational institutions and public institutions to promote RWH awareness.
- In future studies, comparative analyses with other commercial buildings can be conducted, and RWH can be evaluated as an integrated system with gray water recovery.
- Installing rainwater systems during the construction of the building reduces errors and costs.
- Rainwater and sewage systems must be inspected and maintained regularly.
- The quality of harvested rainwater must be checked at specified intervals.
- It should be noted that there may be difficulties and additional costs involved in installing pipes and connections for rainwater that can be used as gray water within the building.
- The use of rainwater as drinking water should be investigated and an economic analysis of the system should be carried out.
- Effects such as algae, bacteria, and odor formation that may occur in storage tanks must be controlled.
- The studies conducted do not include any infrastructure work or calculations related to snow load. In this context, snow load on roofs not covered by regulations may be included in new calculations (such as snow water equivalent).
- Rainwater that exceeds the capacity of the storage tanks must be properly connected to the groundwater and drained away from the building. This will help reduce the hydrostatic pressure of the groundwater

affecting the building. In addition, the groundwater can be replenished by the water discharged from the storage tanks.

- Difficulties in water storage and maintenance can reduce the economic life of the system.
- Since the depreciation periods of these systems are long, great care must be taken during manufacturing and installation.
- The costs that may arise in rainwater systems can be compared for both existing buildings and buildings under construction.

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CHAPTER 3

A COMPREHENSIVE REVIEW AND ANALYSIS OF DUBAI'S FIRE STATISTICS OVER THE PAST DECADE

Fahri YİYİN¹

ABSTRACT

This study explores fire incidents in Dubai over a ten-year period, focusing on their causes and locations based on data provided by the Dubai Data and Statistics Establishment. The analysis reveals notable fluctuations in fire occurrence over the years and emphasizes the predominance of certain building types, particularly commercial structures, in reported incidents. High towers and industrial areas also feature prominently in the data, though to a lesser extent. One of the key challenges identified is the lack of detailed classification regarding the causes of many fires. A significant portion of the records does not specify an exact source, which limits the ability to develop targeted prevention strategies. Among the identified causes, electrical faults and smoking-related factors appear most frequently. The study underscores the importance of improving the quality and depth of fire incident reporting, including the need for root cause documentation and assessment of fire protection systems in affected sites. Better data collection practices would not only enhance fire prevention efforts but also support more accurate risk evaluation and insurance modelling in a rapidly developing urban environment like Dubai.

Keywords: Dubai, fire, data, fire cause analysis, fire risk assessment.

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INTRODUCTION

Fire, which can lead to severe damage including loss of property and assets, has been defined in various regulations and standards to ensure a comprehensive understanding for prevention and control. According to NFPA 921, fire is defined as “A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities.” This description emphasizes fire as a chemical reaction that produces both heat and light.

The classical model used to conceptualize fire is the fire triangle, which identifies three essential components required for a fire to occur: fuel (a combustible material), heat (sufficient to ignite the fuel), and air (typically oxygen). The simultaneous presence of these three elements results in combustion. Variations in oxygen concentration and the chemical properties of both the fuel and the oxidizing agent can directly influence the characteristics and intensity of a fire. In more recent developments, the National Fire Protection Association (NFPA) has expanded the traditional fire triangle by introducing a fourth critical component: the uninhibited chain reaction. This chain reaction refers to the feedback loop in which heat is continually supplied to the fuel, facilitating the production of flammable gases that sustain the flame. As noted, “This chain reaction is the feedback of heat to the fuel to produce the gaseous fuel used in the flame. In other words, the chain reaction provides the heat necessary to maintain the fire.” The incorporation of this fourth element results in what is known as the fire tetrahedron, offering a more accurate representation of fire behaviour, especially in the context of modern suppression techniques. Specifically, this model explains how clean agent halon replacements suppress fires by disrupting the uninhibited chain reaction of combustion, thereby halting the fire at a molecular level.

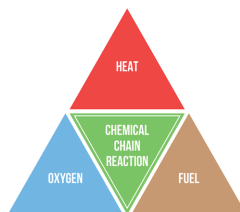


Figure 1. Fire Tetrahedron

Such an expanded understanding not only enhances fire science but also supports the development of more effective fire suppression strategies,

contributing significantly to safety and risk management in both industrial and residential settings.

FIRE RISK AND FIRE STATISTICS

Fire risk assessment is a systematic process aimed at evaluating the potential dangers that unwanted fires pose to both human life and property. It follows the foundational principles of risk assessment common to a broad range of disciplines, adapting them specifically to the context of fire safety. At its core, the process involves identifying possible fire scenarios and estimating both their likelihood of occurrence and the severity of their potential consequences. In its simplest form, a fire risk assessment focuses on a single unwanted fire scenario, analysing the probability that it might occur alongside the potential outcomes. However, more robust assessments go further by considering a comprehensive set of possible fire events, each with its own range of consequences. This approach allows for a more accurate and effective understanding of fire-related risks, especially in complex environments such as large buildings or industrial facilities.

Central to this methodology is the concept of the fire scenario, which will be elaborated upon in the following section. A fire scenario encompasses a sequence of events, including ignition, fire development, and its interaction with safety systems and occupants. The success or failure of specific fire protection measures (such as detection systems, suppression mechanisms, or evacuation protocols) directly influences how the scenario unfolds. To illustrate, consider the evaluation of life safety risk for building occupants under a particular fire scenario. In this context, the expected risk to life can be quantitatively expressed as: Expected Risk to Life = $P \times C$.

Here, P represents the probability of the specific fire scenario occurring, while C denotes the expected number of fatalities resulting from that scenario. This formulation provides a measurable framework to compare various risks and prioritize mitigation strategies accordingly. By systematically analysing both the likelihood and consequences of fire events, fire risk assessment serves as a critical tool for informed decision-making in fire safety planning. It supports the identification of vulnerabilities, the optimization of protection systems, and ultimately contributes to the safeguarding of lives and assets.

Within the framework of the Confederation of Fire Protection Associations Europe (CFPA), fire hazard is defined as “the potential for loss of life (or injury) and/or damage to property by fire.” This definition emphasizes not only the threat to human life but also the potential destruction of physical assets, underscoring the dual nature of fire hazards in safety planning and

risk mitigation efforts. Effective fire risk assessment is a critical component of fire safety management, enabling the identification and control of conditions that could lead to fire-related incidents. According to CFPA guidance, the fire risk assessment process is structured into a series of systematic procedures aimed at evaluating and mitigating potential hazards in both residential and non-residential environments.

The key stages of the fire risk assessment process, as outlined by CFPA, include:

1. Identify Hazards - The first step involves recognizing conditions that may cause or contribute to the ignition and spread of fire, including flammable materials, ignition sources, and structural vulnerabilities.
2. Identify People and Property Exposed to a Hazard - This stage assesses who and what may be at risk in the event of a fire, such as occupants, visitors, and valuable property or infrastructure.
3. Remove and Reduce the Fire Hazards - Once hazards are identified, measures must be taken to eliminate or minimize them through engineering controls, behavioural protocols, or administrative changes.
4. Determine Level of Risk / Assign Risk Categories - Risk is evaluated based on the likelihood of fire occurrence and the severity of its consequences, with hazards categorized according to the level of threat they pose.
5. Decide if the Measures of Risk Reduction are Reliable - An assessment is conducted to determine whether implemented controls and safety measures (e.g., fire alarms, extinguishers, evacuation procedures) are sufficient and dependable.
6. Decide if the Residual Risk is Tolerable - After mitigation strategies are in place, the remaining (residual) risk must be evaluated. If it remains unacceptable, further interventions are required.
7. Review of the Adequacy of the Action Plan - The final stage involves a critical review of the overall fire safety strategy to ensure it is comprehensive, up-to-date, and aligned with regulatory standards.

This structured approach ensures a holistic understanding of fire hazards and promotes proactive risk management. By systematically identifying, assessing, and controlling fire risks, organizations can significantly reduce the potential for harm and enhance resilience against fire-related incidents.

Conducting on-site assessments for fire risk plays a critical role in reducing the likelihood of potential fire incidents. Direct observation and localized evaluation allow for the identification of specific hazards that may not be apparent through general guidelines or theoretical analysis. However, in practice, performing detailed fire risk analyses for every individual building is not always feasible due to limitations imposed by existing standards, regulations, and resource constraints. Given these challenges, fire statistics have become an indispensable tool for fire risk management. This section of the study emphasizes the value and necessity of utilizing statistical fire data to compensate for gaps in building-specific assessments. Aggregated data on fire incidents (including frequency, causes, locations, and outcomes) provides a broader understanding of risk patterns, which can guide the development of targeted prevention strategies and inform policy decisions. In the absence of comprehensive individual building evaluations, statistical analysis serves as a practical and evidence-based approach to improving overall fire safety.

Historical fire data collected within a specific urban area offers significant value not only for public fire safety planning but also for the insurance industry. For municipalities, the analysis of past fire incidents (including their location, cause, frequency, and severity) helps identify vulnerable zones and high-risk behaviors. This enables targeted prevention strategies, efficient allocation of emergency resources, and informed policy development, all of which contribute to a safer and more resilient urban environment.

From the perspective of the insurance sector, such data is equally vital. Insurers rely on accurate historical fire records to assess risk levels for specific properties or neighborhoods, calculate premiums more precisely, and develop appropriate coverage models. Identifying trends in fire frequency and severity allows underwriters to adjust their risk models and forecast potential losses with greater accuracy. Furthermore, this information supports efforts to incentivize fire prevention measures among property owners through risk-based pricing and tailored insurance solutions. In essence, the integration of historical fire data into both urban safety planning and insurance practices enhances risk awareness, reduces economic losses, and promotes more sustainable and proactive risk management across public and private sectors.

DUBAI'S 10 YEAR FIRE STATISTICS

Fire data covering a ten-year period for Dubai, a constituent emirate of the United Arab Emirates, was sourced from the Dubai Data and Statistics Establishment. This study encompasses the years 2015 through 2024 and provides a comprehensive analysis of fire incidents reported within this

timeframe. The analysis includes the total number of fires, their distribution across different building types, and an examination of the primary causes identified for these fire events. By evaluating these factors, the study aims to offer insights into fire risk patterns and inform future fire prevention and safety strategies within the region.

- 2015 Fire Statistics

In the year 2015, a total of 424 fire incidents were recorded in Dubai. Among these, 140 occurred in commercial establishments, while 107 took place in residential units, including villas and houses. Additionally, 81 fires were reported in buildings with multiple floors. High-rise towers and transportation-related fires were the least frequent, with 4 and 8 incidents respectively. Fires in industrial structures were documented at 13 cases.

Table 1. 2015 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	107
Multiple Floors (Buildings and Apartments)	81
Commercial Establishment	140
Governmental Establishment	11
Industrial Establishment	13
Transportation (Marine/Air)	8
Buildings Under Construction	32
High Towers	4
Waste and Rubbish	14
Other Location	14

Of the total fires that year, the causes of 259 incidents could not be determined due to the absence of reports or insufficient information provided to fire experts. Among the identified causes, the most common were electric sparks, followed by cigarettes, burning candles, and cases of inflammation.

Table 2. 2015 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	259
Leakage of Fuel/ Oil/ Gas	6
Cigarette	24
Heat Source	5
Electric Spark	70
Burning Candle	15
Matchstick	2
Flying Sparks	4
Inflammation	14
Cooking Gas Leakage	-
Mechanical Fault	1
Left Cooking Pot	4
Unspecified	-
Other Reasons	20

- 2016 Fire Statistics

In 2016, a total of 486 fire incidents were officially recorded, occurring across various types of buildings and facilities. Most of these fires took place in commercial establishments, accounting for 172 cases. Residential units followed with 117 reported incidents, while buildings with multiple floors, such as apartment complexes, experienced 98 fires. Notably, transportation facilities and high-rise towers recorded the lowest number of fire incidents, suggesting either more effective fire prevention measures or lower risk exposure in these areas. Additionally, 11 fires were reported in industrial structures, a relatively low figure compared to the more frequently affected categories.

Table 3. 2016 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	117
Multiple Floors (Buildings and Apartments)	98
Commercial Establishment	172
Governmental Establishment	22
Industrial Establishment	11
Transportation (Marine/Air)	5
Buildings Under Construction	27
High Towers	7
Waste and Rubbish	17
Other Location	10

A detailed examination of the 2016 fire incidents reveals notable inconsistencies in the reported figures concerning fire causes and locations. While the total number of recorded fire incidents by location is stated as 486, only 241 fires have been categorized by cause. In an effort to verify the data, the Annual Report 2016 published by the UAE Ministry of Interior, General Command of Civil Defence, Directorate General of Dubai Civil Defence was reviewed. According to the report, only 48 fires had a clearly identified cause. Additionally, 227 cases were marked as inspection in process, indicating ongoing investigations. Electrical short circuits accounted for 63 fires, while 19 were attributed to cigarette-related negligence. In 121 cases, fire experts concluded that no further investigation was necessary, and in 15 instances, they were unable to determine the cause. Furthermore, among the 241 incidents documented in the tabular dataset, 92 fires had not been reported to fire investigators. Within this dataset, 72 fires were attributed to electric sparks and 21 to cigarettes.

Table 4. 2016 Fire Accidents by Reason (Dubai Data and Statistics Establishment)

Reason	Recorded Fire Cases
Fire Expert is Not Informed	92
Leakage of Fuel/ Oil/ Gas	6
Cigarette	21
Heat Source	6
Electric Spark	72
Burning Candle	2
Matchstick	1
Flying Sparks	4
Inflammation	11
Cooking Gas Leakage	-
Mechanical Fault	-
Left Cooking Pot	5
Unspecified	15
Other Reasons	6

Table 5. 2016 Fire Accidents by Reason (Annual Report 2016)

Causes of Fire	Fire Cases
Inspection in Process	227
Affected, not interested to call fire expert for inspection	121
Electrical Short Circuit	63
Cigarette Guts	19
Fire expert unable to identify the cause of fire	15
Cooking Oil Ignition	6
Gas Cylinder Leakage	6
Direct Thermal Source	6
Arson Fire	4
Welding Spark Disperse	4
Cooking Fat Ignition	2
Candle Flame	2
Fumigator Left Inside the Cupboard	2
Chemical Material Self Ignition	1
Iron Box Left On	1
Cooking Pan Left on Burner	1
Matches or Lighter	1

- 2017 Fire Statistics

In 2017, a total of 420 fire incidents were officially recorded across various property types in Dubai. The highest number of fires occurred in commercial establishments, accounting for 138 cases. This was followed by 118 incidents in residential units and 81 in multi-storey buildings such as apartment complexes. Notably, the number of fires in industrial structures increased to 18, reflecting a slight rise compared to the previous year. The transportation sector, on the other hand, recorded the lowest number of fire incidents, continuing its trend as the least affected category. These figures underscore the ongoing vulnerability of commercial and residential zones to fire hazards, while also pointing to a growing need for enhanced safety protocols in industrial environments.

Table 6. 2017 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	118
Multiple Floors (Buildings and Apartments)	81
Commercial Establishment	138
Governmental Establishment	14
Industrial Establishment	18
Transportation (Marine/Air)	1
Buildings Under Construction	24
High Towers	8
Waste and Rubbish	13
Other Location	5

In 2017, a significant number of fire incidents (282 cases) could not be conclusively investigated due to the absence of reports or notifications to fire experts. This lack of expert input highlights a persistent issue in data collection and incident reporting. Among the identified causes, 64 fires were attributed to electric sparks. An additional 29 incidents were classified under unknown or other causes, indicating either insufficient information or complex origin points. Moreover, 13 fires were linked to careless cigarette disposal, while 9 incidents were reported to have resulted from direct heat sources.

Table 7. 2017 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	282
Leakage of Fuel/ Oil/ Gas	1
Cigarette	13
Heat Source	9
Electric Spark	64
Burning Candle	3
Matchstick	3
Flying Sparks	4
Inflammation	9
Cooking Gas Leakage	-
Mechanical Fault	1
Left Cooking Pot	2
Unspecified	19
Other Reasons	10

• 2018 Fire Statistics

Compared to the preceding three years, 2018 witnessed a significant decline in the total number of recorded fire incidents. That year, 322 fires were officially documented, marking a notable reduction from previous annual figures. Of these, 113 incidents occurred within commercial establishments, maintaining this category as the most affected despite the overall decrease. Residential units accounted for 92 fires, followed by 48 incidents in multi-storey buildings, such as apartment complexes. Fires in governmental establishments and waste/ rubbish areas were minimal, with only 4 cases reported in each. Additionally, 6 incidents were recorded in transportation-related zones and another six in high-rise towers.

Table 8. 2017 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	92
Multiple Floors (Buildings and Apartments)	48
Commercial Establishment	113
Governmental Establishment	4
Industrial Establishment	9
Transportation (Marine/Air)	6
Buildings Under Construction	31
High Towers	6
Waste and Rubbish	4
Other Location	9

In 2018, a total of 211 fire incidents were left unclassified due to the absence of reporting to fire experts, continuing a concerning trend of underreporting seen in previous years. Among the categorized cases, the three most frequent causes of fire were identified as electric sparks, discarded cigarettes, and spontaneous inflammation. Notably, 15 incidents were recorded as unspecified, reflecting uncertainty or insufficient information during documentation. Compared to 2017, the number of electric spark-related fires showed a marked decline of approximately 30%, falling to 45 cases.

Table 9. 2018 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	211
Leakage of Fuel/ Oil/ Gas	3
Cigarette	14
Heat Source	5
Electric Spark	45
Burning Candle	6
Matchstick	1
Flying Sparks	3
Inflammation	9
Cooking Gas Leakage	-
Mechanical Fault	-
Left Cooking Pot	4
Unspecified	15
Other Reasons	6

- 2019 Fire Statistics

In 2019, a total of 329 fire incidents were recorded, representing a slight increase of seven cases compared to the previous year. Commercial establishments remained the most affected category, with 122 fires reported. This was followed by 74 incidents in residential units and 65 in multi-storey buildings. Notably, no fire incidents were reported in the transportation sector during this period. Waste and rubbish areas experienced the lowest number of fires, with only four cases documented.

Table 10. 2019 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	74
Multiple Floors (Buildings and Apartments)	65
Commercial Establishment	122
Governmental Establishment	5
Industrial Establishment	9
Transportation (Marine/Air)	-
Buildings Under Construction	29
High Towers	7
Waste and Rubbish	4
Other Location	14

In 2019, fire experts were unable to determine the causes of 217 recorded fire incidents due to insufficient information or lack of formal reporting. Among the identified cases, electric sparks were once again the leading cause, responsible for 45 incidents. Fires caused by inflammation were reported in 10 cases, while cigarette-related negligence accounted for 8. Additionally, 22 fires were labelled as unidentified, and 8 incidents were attributed to various other causes.

Table 11. 2019 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	217
Leakage of Fuel/ Oil/ Gas	1
Cigarette	8
Heat Source	5
Electric Spark	45
Burning Candle	3
Matchstick	1
Flying Sparks	3
Inflammation	10
Cooking Gas Leakage	-
Mechanical Fault	-
Left Cooking Pot	6
Unspecified	22
Other Reasons	8

- 2020 Fire Statistics

In 2020, a total of 356 fire incidents were officially reported, and the distribution of these incidents across various locations closely mirrored the patterns observed in previous years. Commercial establishments once again accounted for the highest number of fires, with 120 cases recorded. Residential units followed with 92 incidents, while multi-storey buildings, such as apartments, accounted for 67 cases. Fires occurring in buildings under construction were notably recorded at 22 incidents, reflecting the specific risks associated with ongoing construction activities. Additionally, 11 fires were reported in industrial establishments.

Table 12. 2020 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	92
Multiple Floors (Buildings and Apartments)	67
Commercial Establishment	120
Governmental Establishment	9
Industrial Establishment	11
Transportation (Marine/Air)	7
Buildings Under Construction	22
High Towers	8
Waste and Rubbish	8
Other Location	12

In 2020, fire investigation data revealed that 245 incidents could not be examined or classified by fire experts due to insufficient or missing information. Among the categorized cases, electric sparks remained the most prevalent cause, accounting for 48 fire incidents. Additionally, a combined total of 27 fires were classified either as unidentified or attributed to miscellaneous causes that could not be clearly defined.

Table 13. 2020 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	245
Leakage of Fuel/ Oil/ Gas	2
Cigarette	13
Heat Source	4
Electric Spark	48
Burning Candle	2
Matchstick	-
Flying Sparks	6
Inflammation	6
Cooking Gas Leakage	-
Mechanical Fault	-
Left Cooking Pot	3
Unspecified	17
Other Reasons	10

- 2021 Fire Statistics

In 2021, a total of 358 fire incidents were officially recorded. Unlike previous years, where commercial establishments consistently topped the list, the highest number of fires this year occurred in residential units, with 106 cases reported. Commercial establishments followed closely with 100 incidents, marking a shift in the primary location of fire occurrences. Multi-storey buildings ranked third, accounting for 77 fires. Industrial establishments experienced 11 fires (unchanged from 2020) while 17 incidents were reported in buildings under construction. Additionally, eight fires were recorded in the transportation sector, including marine and air-related locations.

Table 14. 2021 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	106
Multiple Floors (Buildings and Apartments)	77
Commercial Establishment	100
Governmental Establishment	12
Industrial Establishment	11
Transportation (Marine/Air)	8
Buildings Under Construction	17
High Towers	7
Waste and Rubbish	8
Other Location	12

In 2021, a total of 217 fire incidents could not be classified due to the lack of reporting to fire experts, continuing a persistent issue in fire cause identification. Among the identifiable causes, electric sparks once again emerged as the leading factor, contributing to 67 fire incidents. This represents an increase of 19 cases compared to the previous year, underscoring the ongoing vulnerability of electrical systems across various property types. Cigarette-related fires ranked second, with 20 recorded incidents.

Table 15. 2021 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	217
Leakage of Fuel/ Oil/ Gas	2
Cigarette	20
Heat Source	8
Electric Spark	67
Burning Candle	3
Matchstick	-
Flying Sparks	3
Inflammation	6
Cooking Gas Leakage	-
Mechanical Fault	-
Left Cooking Pot	5
Unspecified	15
Other Reasons	12

- 2022 Fire Statistics

In 2022, a total of 325 fire incidents were recorded, marking a continued fluctuation in annual fire trends. Commercial establishments once again ranked as the most affected category, with 102 fires reported. Residential units followed closely, accounting for 95 incidents, while multi-storey buildings registered 61 fires, placing them third. Fires in governmental establishments totalled 14, whereas industrial establishments reported only 8 cases one of the lowest figures among all categories.

Table 16. 2022 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	95
Multiple Floors (Buildings and Apartments)	61
Commercial Establishment	102
Governmental Establishment	14
Industrial Establishment	8
Transportation (Marine/Air)	6
Buildings Under Construction	10
High Towers	10
Waste and Rubbish	-
Other Location	19

In 2022, a total of 209 fire incidents remained unclassified due to the absence of reports to fire experts, highlighting the ongoing challenges in data completeness and response coordination. Among the identified cases, electric sparks continued to be the predominant cause, resulting in 64 fires. Cigarette-related fires accounted for 23 incidents, while a combined total of 10 fires were attributed to flying sparks and inflammation. Notably, no fires were reported as having originated from heat sources a unique detail distinguishing this year from previous ones.

Table 17. 2022 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	209
Leakage of Fuel/ Oil/ Gas	1
Cigarette	23
Heat Source	-
Electric Spark	64
Burning Candle	3
Matchstick	1
Flying Sparks	5
Inflammation	5
Cooking Gas Leakage	1
Mechanical Fault	-
Left Cooking Pot	1
Unspecified	-
Other Reasons	12

- 2023 Fire Statistics

In 2023, a total of 358 fire incidents were recorded matching the figure observed in 2021. Commercial establishments accounted for the highest number of fires, with 95 cases documented. Notably, fire incidents in multi-storey buildings and residential units were reported at an equal level, with 87 cases each. Governmental establishments experienced 16 fires, while industrial establishments recorded 15, marking the highest number of industrial fires since 2017. Of particular significance, 11 fires were reported in high-rise towers making it the highest number recorded in this category since 2015.

Table 18. 2023 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	87
Multiple Floors (Buildings and Apartments)	87
Commercial Establishment	95
Governmental Establishment	16
Industrial Establishment	15
Transportation (Marine/Air)	11
Buildings Under Construction	14
High Towers	11
Waste and Rubbish	-
Other Location	22

As in 2022, a total of 209 fire incidents in 2023 remained unclassified due to insufficient information provided to fire experts. Among the documented cases, electric sparks continued to be the leading identified cause, resulting in 68 fires. An additional 39 incidents were categorized as either unidentified or caused by miscellaneous factors that could not be clearly defined. Combined, heat sources and cigarette-related fires accounted for 22 incidents.

Table 19. 2023 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	209
Leakage of Fuel/ Oil/ Gas	1
Cigarette	11
Heat Source	11
Electric Spark	68
Burning Candle	1
Matchstick	1
Flying Sparks	4
Inflammation	4
Cooking Gas Leakage	3
Mechanical Fault	-
Left Cooking Pot	6
Unspecified	29
Other Reasons	10

- 2024 Fire Statistics

In 2024, the number of recorded fire incidents dropped to 280, marking the lowest annual total in the past decade. This decline suggests possible improvements in fire prevention, public awareness, and emergency response efficiency. Of the total fires, 73 occurred in residential units, followed closely by 71 in multi-storey buildings and 69 in commercial establishments categories that have historically represented the highest fire risk. Industrial establishments accounted for 12 incidents, while high-rise towers recorded 10 fires. Governmental establishments experienced the fewest fires, with only 8 incidents reported throughout the year.

Table 20. 2024 Fire Accidents by Location

Location	Recorded Fire Cases
Residential Units	73
Multiple Floors (Buildings and Apartments)	71
Commercial Establishment	69
Governmental Establishment	8
Industrial Establishment	12
Transportation (Marine/Air)	10
Buildings Under Construction	11
High Towers	10
Waste and Rubbish	-
Other Location	16

In 2024, a total of 159 fire incidents could not be classified due to the lack of information provided to fire experts, continuing the longstanding issue of underreported fire causes. Additionally, 13 fires were recorded as unidentified, while 7 were attributed to miscellaneous or unspecified causes. Electric spark remained the most frequent identifiable cause, responsible for 61 incidents, reinforcing its position as a persistent ignition hazard across different property types. This was followed by 13 fires linked to cigarette use and 10 caused by heat sources. Although 2024 marked the lowest total number of fires in the past decade, the distribution of causes suggests that common preventable factors (particularly electrical faults and human negligence) continue to play a central role in fire outbreaks.

Table 21. 2024 Fire Accidents by Reason

Reason	Recorded Fire Cases
Fire Expert is Not Informed	159
Leakage of Fuel/ Oil/ Gas	2
Cigarette	13
Heat Source	10
Electric Spark	61
Burning Candle	2
Matchstick	-
Flying Sparks	5
Inflammation	4
Cooking Gas Leakage	1
Mechanical Fault	-
Left Cooking Pot	3
Unspecified	13
Other Reasons	7

**OVERVIEW AND COMPARISON OF FIRE CASES
(2015-2024)**

Between 2015 and 2024, a total of 3,658 fire incidents were recorded, categorized by the type of building or establishment in which they occurred. Of these, 32% took place in commercial establishments, while 26.3% occurred in residential units. Fires in multi-floor structures such as buildings and apartment complexes accounted for 20.1% of the total.

Until 2023, the number of fire incidents occurring in commercial establishments consistently remained above 100. However, a noticeable decline was observed in the following years, with 95 incidents recorded in 2023 and 69 in 2024. This downward trend in fire occurrences within commercial structures has directly contributed to the overall reduction in total fire incidents in 2024. The significant decrease in fire frequency among these high-traffic, business-oriented facilities may reflect the impact of improved fire prevention measures, regulatory compliance, or operational shifts within the commercial sector.

The areas with the lowest incidence of fires during this period included transportation sectors (marine and air), waste and rubbish zones, and high-rise towers, with shares of 1.7%, 1.9%, and 2.1% respectively. Industrial

establishments experienced 117 fire incidents over the ten-year period, representing 3.2% of the total.

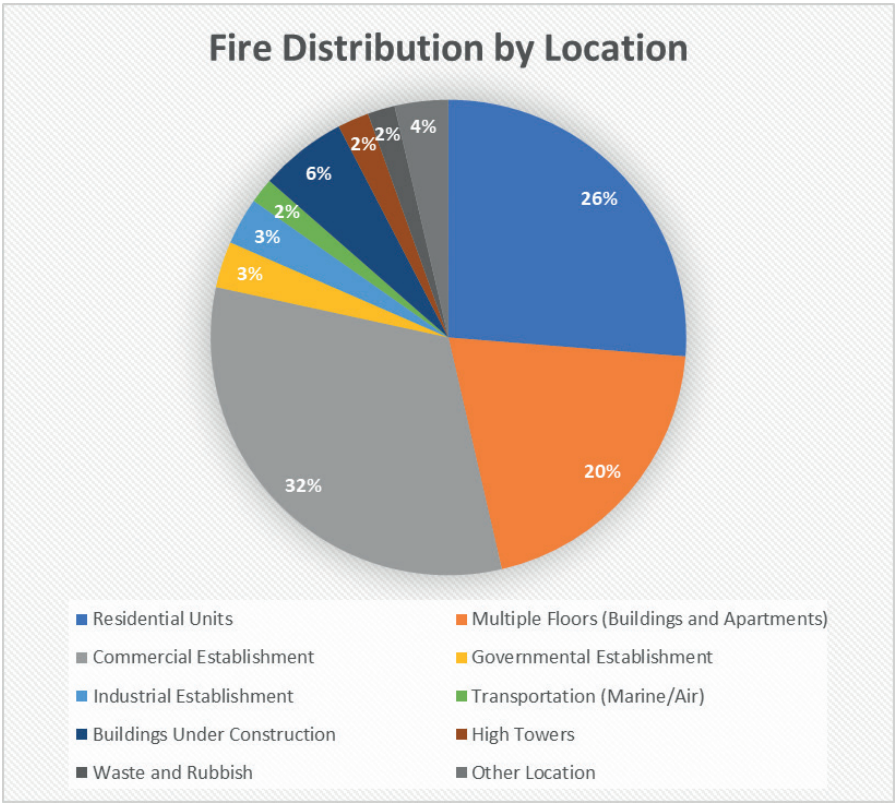


Figure 2. Fire Distribution by Location (2015-2024)

An annual analysis of fire frequency revealed specific years with increases and decreases relative to the previous year. Notable increases were observed in 2016, 2019, 2020, 2021, and 2023. The most significant rise occurred between 2015 and 2016, with a 14.6% increase. Conversely, the years 2017, 2018, 2022, and 2024 recorded declines in the number of fires. The sharpest decrease was registered between 2017 and 2018, with a drop of 23.3%. When comparing the beginning and end of the observed period, the number of fire incidents in 2024 showed a significant decrease of 34% compared to 2015, highlighting a notable long-term downward trend.

Table 22. Changes in Fire Numbers by Year

Years	Fire Cases	Change
2024	280	21.8%
2023	358	10.2%
2022	325	-9.2%
2021	358	0.6%
2020	356	8.2%
2019	329	2.2%
2018	322	-23.3%
2017	420	-13.6%
2016	486	14.6%
2015	424	-

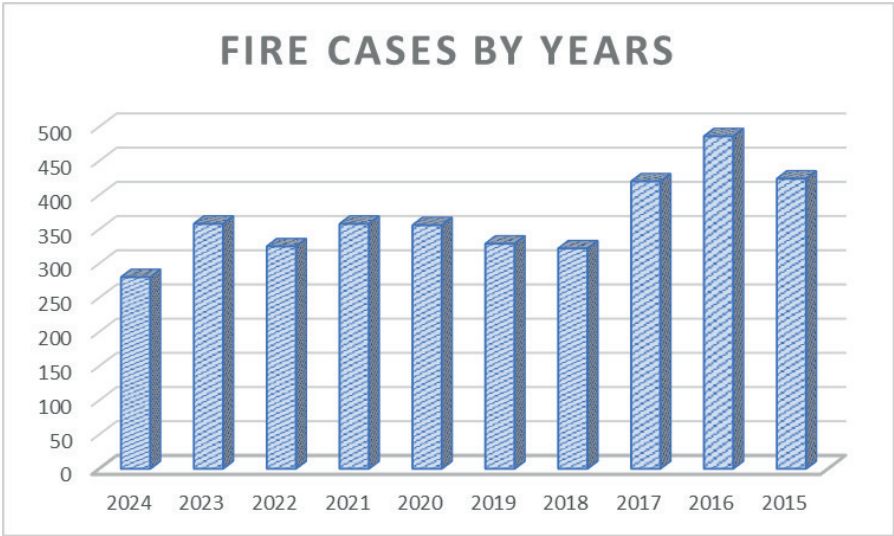


Figure 3. Fire Causes by Years (2015-2024)

An average of approximately 366 fire incidents per year was recorded between 2015 and 2024. The number of fires in 2015, 2016, and 2017 exceeded this average, whereas the years 2018 through 2024 consistently fell below it. A year-by-year examination of fire locations revealed shifting patterns in the types of premises most frequently affected. Notably, in both 2021 and 2024, the highest number of fire incidents occurred in residential units. In contrast, during the remaining years of the period, commercial establishments were the most affected areas. Over the ten-year period from 2015 to 2024, industrial

establishments experienced an average of 11.7 fire incidents per year. The highest number of fires in this category occurred in 2017, while the lowest was recorded in 2022.

Table 23. Fire Accidents by Location (2015-2024)

Location	2024	2023	2022	2021	2020	2019	2018	2017	2016	2015	Total	Percentage
Residential Units	73	87	95	106	92	74	92	118	117	107	961	26.3
Multiple Floors	71	87	61	77	67	65	48	81	98	81	736	20.1
Commercial Establishment	69	95	102	100	120	122	113	138	172	140	1171	32.0
Governmental Establishment	8	16	14	12	9	5	4	14	22	11	115	3.1
Industrial Establishment	12	15	8	11	11	9	9	18	11	13	117	3.2
Transportation (Marine/Air)	10	11	6	8	7	-	6	1	5	8	62	1.7
Buildings Under Construction	11	14	10	17	22	29	31	24	27	32	217	5.9
High Towers	10	11	10	7	8	7	6	8	7	4	78	2.1
Waste and Rubbish	-	-	-	8	8	4	4	13	17	14	68	1.9
Other Location	16	22	19	12	12	14	9	5	10	14	133	3.6
Total	280	358	325	358	356	329	322	420	486	424	3658	100.0

An analysis of fire causes over the ten-year period revealed that detailed information was not available for 61.5% of the recorded incidents. An additional 7.2% were classified as either other or unknown causes. After excluding these unspecified cases, the most prominent identified causes were ranked accordingly. Electrical sparks emerged as the leading cause, accounting for 56.6% of the identified incidents, followed by cigarette-related fires at 15%, and spontaneous inflammation at 7.3%. Combined, electrical and smoking-related causes represented over 70% of the total identifiable fire sources, emphasizing the critical need to focus preventive efforts on electrical installations and designated smoking areas.

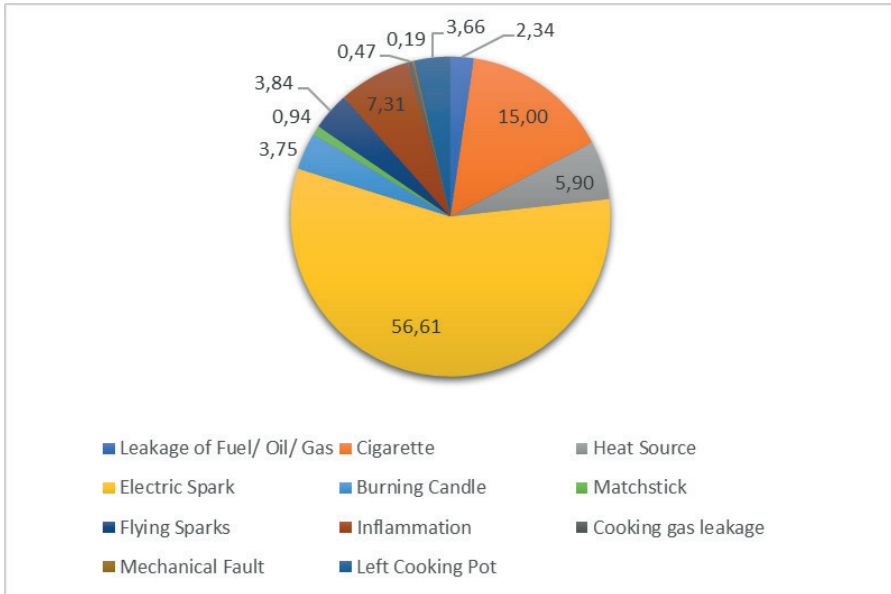


Figure 4. Classification of Fires According to Their Causes (Excluding Unidentified Fires)

In line with these findings, Chapter 6 of NFPA 30 highlights several ignition sources that require particular attention. These include open flames, lightning, hot surfaces, radiant heat, smoking, cutting and welding operations, spontaneous ignition, frictional heat or sparks, static electricity, electrical sparks, stray currents, and heating equipment such as ovens and furnaces. Addressing these hazards through targeted safety measures could significantly reduce the likelihood of future fire incidents. Regular maintenance of electrical systems, the use of fire-resistant electrical components, and the installation of fire suppression systems specifically designed for electrical areas can significantly reduce the number of fire incidents caused by electrical faults. In addition to these measures, it is essential to ensure that combustible materials are not stored around electrical panels, and that all electrical systems are accessed and managed exclusively by authorized personnel.

CONCLUSION

The initial phase of this study, which focuses on fire incidents in Dubai over the past decade, addresses the definition of fire, the identification of fire risk, and the importance of reliable fire data. In the subsequent sections, annual data published by the Dubai Data and Statistics Establishment between 2015 and

2024 have been analysed. These datasets include information on the location and causes of each recorded fire incident.

The year 2016 witnessed the highest number of fire incidents, totalling 486. However, cause-related data for that year accounted for only 241 cases. To verify this discrepancy, the Annual Report 2016 issued by the UAE Ministry of Interior was reviewed, revealing that 481 fire incidents had documented causes—highlighting potential inconsistencies in source reporting. On the other end of the spectrum, 2024 recorded the lowest number of fires, with 280 incidents.

In terms of location, commercial establishments accounted for the largest share of incidents at 32%, while the lowest percentage was associated with transportation-related settings (marine and air), at just 1.7%. When fire causes were analysed, it was found that approximately 69% of the incidents lacked classification. Among the identified causes, electrical sparks ranked first, followed by cigarette-related sources. These patterns reinforce the critical importance of accurately and consistently analysing both the origin and the type of environment in which fires occur.

Despite the availability of public fire data, the current scope appears insufficient for a comprehensive risk assessment. Based on the findings, several key areas for improvement have been identified:

- **More Granular Classification of Locations:** Categorizing fire incidents into subtypes within each location category, especially for industrial and commercial establishments, would enhance sector-specific risk assessments. Recording incident data by industrial sector (e.g., chemical, storage, metal, textile, plastic) would not only improve targeted fire prevention but also contribute valuable insights to industries such as insurance.
- **Improved Documentation of Root Causes:** More than 2,300 out of 3,658 recorded fires in the ten-year period lack clearly defined causes. Conducting root cause analyses and ensuring on-site post-incident investigations are documented by trained controllers would strengthen the reliability of the data. Better data accuracy could directly contribute to reducing fire risks by enabling preventive strategies based on known triggers.
- **Inclusion of Human and Economic Loss Data:** In addition to tracking the number of incidents per year, it is essential to record casualties and property losses to fully understand the impact of fires.

- **Strengthening Public–Private Partnerships:** Encouraging cooperation between public authorities and the private sector, particularly in the insurance field, can help promote fire risk coverage. Emphasizing the importance of fire insurance for various building types would be a step toward improved financial resilience.
- **Recording the Status and Effectiveness of Fire Protection Systems:** Data should include information on the presence and functionality of fire safety systems such as smoke detectors, sprinkler systems, fire extinguishers, emergency exits, and fire-rated doors. Whether these systems were installed, regularly maintained, and functional during the fire (e.g., whether sprinklers helped suppress the fire or if alarms provided early warning) is critical for setting and refining fire safety standards. For the insurance industry, such data also enable more precise risk modelling and premium structures. Moreover, identifying systemic failures may guide future regulation or incentive schemes.

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CHAPTER 4

IMPACTS OF CLIMATE CHANGE IN EASTERN ANATOLIA REGION: ANALYSIS OF TEMPERATURE AND HUMIDITY TRENDS IN MALATYA PROVINCE

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Abstract

This study analyzes long-term temperature and relative humidity data from four meteorological stations in the region (Arapgir, Darende/Balaban, Doğanşehir and Malatya Center) to examine the climatic changes in Malatya province, located in the Eastern Anatolia Region of Turkey. The main data source of the study is the monthly average temperature (°C) and relative humidity (%)

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values provided by the Turkish General Directorate of Meteorology (MGM) covering a 35-year period between 1985 and 2019. In the determination of climatic trends, statistical significance was evaluated using the nonparametric Mann-Kendall test, and the direction and magnitude of the trends were calculated by Sen's Slope method. According to the results of the analysis, temperature values at Arapgir station showed a statistically significant increasing trend with a confidence level above 90%. The same station's relative humidity readings showed a notable decline, with a 94.1% confidence level. At the Darende/Balaban and Doğanşehir stations, we observed some temperature and humidity changes, but these were not statistically significant because they were below the 90% confidence interval. The temperature data at Malatya Central station, on the other hand, displayed a notable upward trend with a 92.5% confidence level, whereas the relative humidity data showed a sharp decline with a remarkable 99.8% confidence level. In general, it was found that temperatures increased and relative humidity values decreased in Malatya province during the 35-year period. These findings show that climate change is gradually increasing its impact in the form of warming and drying in the region. These changes have the potential to have profound impacts on agricultural production patterns, sustainability of water resources, balance of natural ecosystems and rural living conditions. Especially in regions such as Malatya, where agricultural production has a significant share in the economy, the long-term impacts of drought and temperature increases due to climate change need to be carefully evaluated. This study provides a scientific database that will contribute to the development of adaptation strategies for policy makers and researchers by revealing the impacts of climate change at the local scale. In future studies, it is recommended to examine in detail the possible impacts of these trends on the hydrological cycle, agricultural productivity and biodiversity.

Keywords: Mann-Kendall, Sen's Slope, trend analysis, temperature, relative humidity, climate change.

1. Introduction

The effects of climate change are becoming increasingly apparent on a global and regional scale. In this context, the analysis of long-term trends in meteorological parameters provides important information in many areas, such as environmental management, agricultural production, and urban planning (Garba and Udokpoh, 2023). In particular, variables such as temperature, relative humidity, and precipitation are among the fundamental indicators of the climate system, and changes in these parameters have direct effects on both natural systems and human health (Adedapo, 2020). In this context, the

Mann-Kendall test and Sen's slope estimator, developed for trend detection on time series data, are widely used in the literature (Eryürük and Eryürük, 2024). But in addition to traditional techniques, more thorough and sensitive tools like Sen's novel trend analysis (ITA) method have also started to be employed recently.

Recent studies investigating the impacts of climate change on drought characteristics indicate that hydro climatic variables are undergoing significant spatial and temporal transformations particularly in arid and semi arid regions. Touhedi et al. (2023) conducted a comprehensive nationwide assessment of the areal distribution and trend behavior of different drought classes in Türkiye by jointly applying the Mann Kendall trend analysis and ITA methods. The findings revealed decreasing tendencies in humid and very wet drought classes across many regions whereas increasing patterns were identified in the near normal drought category. Notably significant variations were detected in moderately dry and very dry drought classes in several provinces of Eastern Anatolia indicating that regional climate variability is evolving through a nonlinear and multidimensional transformation process. The study emphasized that drought classes exhibit not only temporal trend differences but also spatial redistribution characteristics suggesting that climate change impacts may lead to heterogeneous regional responses. This highlights the necessity of evaluating temperature increases atmospheric moisture reductions and precipitation regime shifts in an integrated manner. Furthermore alterations in drought class distributions were reported to have important implications for water resources sustainability agricultural productivity and ecosystem resilience. Therefore long term trend analysis of regional meteorological parameters is considered a critical scientific requirement for climate risk assessment and the development of effective adaptation strategies. Agbo et al. (2023) compared Sen's method with the Mann-Kendall test in their study on atmospheric parameters in various climate regions of Nigeria. They demonstrated that Sen's method can reveal trends in low, medium, and high value ranges and, in this regard, offers more insight for engineering applications. Comparative analysis of these approaches yields valuable insights into statistical significance as well as the appropriate physical interpretation of trends. In a comprehensive study conducted in the northeast of the Aras Basin, Topçu et al. (2025) performed a multiparameter drought assessment using the Aggregate Drought Index (ADI) and Innovative Polygon Trend Analysis (IPTA) methods, and determined that significant drought trends emerged, especially in winter and summer seasons. Furthermore, the lack of complete agreement between different drought indices highlighted the importance of selecting indices appropriate to regional climate characteristics. The results obtained in the study show that the effects of climate

change on the hydrological cycle are complex and multidimensional, and therefore trend analyses should be supported by multiparameter approaches. Körük et al. (2023) investigated the long-term trend behavior of monthly precipitation data in the Susurluk Basin located in northwestern Turkey in terms of climate change impacts. In the study precipitation records from nine meteorological stations covering the period 1970-2019 were analyzed using Innovative Polygon Trend Analysis IPTA with star graph concept and Improved Visualization Innovative Trend Analysis IV ITA methods and the results were compared with the classical Mann Kendall MK test. The findings indicated that the MK method detected statistically significant trends only in a limited number of months whereas graphical innovative approaches provided more sensitive trend identification especially for low and high value ranges. According to the results precipitation tended to increase during autumn months while decreases in precipitation during dry periods were emphasized as a potential pressure on agricultural water demand and water quality. Furthermore monthly shifts in precipitation regime were identified and it was highlighted that climate change influences not only mean values but also the behavior of extreme hydro-meteorological events. These results underline the importance of multidimensional trend approaches in hydro-meteorological time series analysis. Hadi et al. (2018) investigated the long term spatiotemporal trend behavior of precipitation and temperature variables across Iran. The study utilized a large scale meteorological dataset covering the period 1966-2013 and trend analyses were performed using the Mann Kendall MK test and Sen's Slope estimator. The results revealed significant increasing trends in temperature values in many parts of the country while precipitation trends exhibited strong spatial variability. It was emphasized that precipitation decreases particularly in arid and semi arid regions may exert considerable pressure on water resources sustainability and agricultural productivity. Moreover increasing temperature levels may enhance evaporation rates leading to alterations in hydrological cycle processes and higher drought risk levels. The study also highlighted that evaluating climatic trends in both temporal and spatial dimensions is essential for a more accurate interpretation of climate change impacts.

In this study climate trend analysis was conducted using monthly average temperature and relative humidity data obtained from four meteorological stations located in Malatya province in eastern Türkiye. Long term observational records from Malatya Central Doğanşehir Arapgir and Darandere Balaban stations were evaluated in order to reveal regional climate variability characteristics. The direction and rate of change of the trends were determined using the Sen's Slope method while their statistical significance was assessed through the Mann Kendall MK test. The combined use of these two approaches enables

a reliable determination of both the existence and magnitude of climatic trends. The primary objective of the study is to identify long term temperature and humidity variations specific to the Malatya region and to scientifically evaluate their potential impacts on hydrological cycle processes evaporation dynamics drought risk and water resources sustainability. In semi arid climatic environments increasing temperature and decreasing humidity trends may have significant consequences for agricultural productivity ecosystem balance and urban water demand. Therefore station based trend assessments contribute to a more accurate understanding of regional climate change impacts. Furthermore the findings are expected to provide a scientific basis for the development of regional climate adaptation strategies drought early warning systems and sustainable water management policies. In this respect the results of the study may serve as a valuable reference for both engineering practices and climate policy planning processes.

2. Material and Methods

Study area

This study was conducted in Malatya Province, located in the Eastern Anatolia Region of Turkey. The total area of the province is approximately 12,259 km², and the provincial capital is located at an average altitude of 948-950 m above sea level. The region has a semi-arid continental climate, with annual precipitation typically ranging from 350-500 mm (Climate-Data.org, 2025). Additionally, the annual average temperature is calculated to be approximately 14-14.5°C, with hot and dry summers and cold and snowy winters (Climate-Data.org, 2025; WorldWeatherOnline, 2025). Given these climatic characteristics, Malatya Province provides a suitable geographical framework for analyzing long-term temperature and humidity trends. Due to its geographical location Malatya province lies in the transition zone between the temperate Mediterranean climate and the cold continental climate which results in remarkable climate variability characteristics. According to the Köppen climate classification the region belongs to the BSk category and exhibits semi arid steppe climate features. Long term meteorological observations indicate that extreme temperature and extreme precipitation events occasionally influence the region. For instance the recorded maximum temperature of 42.7 °C and minimum temperature of -22.2 °C highlight the significant thermal amplitude of the area. Moreover the occurrence of maximum daily precipitation reaching 52.6 mm and snow depth values up to 67 cm indicates a highly variable hydrological response in the region. In addition increasing population density and urbanization processes in the city center have led to considerable expansion

of stormwater drainage systems. This situation may contribute to elevated urban flood risk levels particularly during intense rainfall events. Therefore considering both natural climate dynamics and anthropogenic influences Malatya province represents a representative and suitable study area for long term temperature and humidity trend analysis (Çırağ and Firat, 2023).

Mann-Kendall and Sen' Slope methods

Nonparametric methods are often preferred in determining trends in climate time series due to their ability to handle seasonalities, outliers, and non-normal distributions in data sets. In this context, the Mann-Kendall (MK) trend test and Sen's Slope estimator are two complementary methods widely used in the literature.

The Mann-Kendall test was first developed by Mann (1945) and later by Kendall (1975). This test is a non-parametric hypothesis test that evaluates whether there is a significant increase or decrease in the ordered values of a time series. The test statistic S is calculated based on the signs of the differences between all observation pairs. If there is a positive trend, $S > 0$, and if there is a negative trend, $S < 0$. The test is converted to a Z score under the null hypothesis (H_0 : no trend) assuming that the S statistic is approximately normally distributed, and the significance level is determined (Amwata et al., 2016; Fattah et al., 2024).

However, the MK test only detects the presence of a trend, it does not determine its magnitude. At this point, Sen's Slope estimator, developed by Sen (1968), comes into play and allows the trend value to be estimated as the median slope. The slope is calculated for each pair of observations, and the median value indicates the direction and magnitude of the overall trend. This approach preserves the robustness of the data against outliers (Zhang et al., 2025).

When both methods are used together, they enable a comprehensive assessment of both the statistical significance and quantitative magnitude of trends in climate data. Therefore, in this study, the Mann-Kendall and Sen's Slope methods were applied together to analyze long-term changes in temperature and relative humidity data for the province of Malatya (Amwata et al., 2016; Fattah et al., 2024; Zhang et al., 2025).

3. Results and Discussions

The results of trend analyses conducted on monthly average temperature and relative humidity data from 1985 to 2019 for the four meteorological

stations analyzed in the study are presented in both graphical and tabular formats. The analyses were performed using the MKS Trend Analysis Tools program (Schneider, M.R. and Lang, G.B., 2021). The direction and statistical significance of climatic trends were assessed using the Mann-Kendall test, while the magnitude of the trends was calculated using Sen's Slope method. In the graphs, blue lines represent monthly average temperature ($^{\circ}\text{C}$), while orange lines represent monthly average relative humidity (%) values. Temperature and humidity trends for each station are shown separately in graphs, while the statistical analysis results for all stations are presented collectively in Table 1 to enable comparison. In addition to the statistical evaluation, visual inspection of trend graphs provides important insights regarding the temporal persistence and variability of climatic parameters. Such graphical interpretation supports the understanding of gradual warming or drying signals that may not always be fully captured by statistical indicators alone.

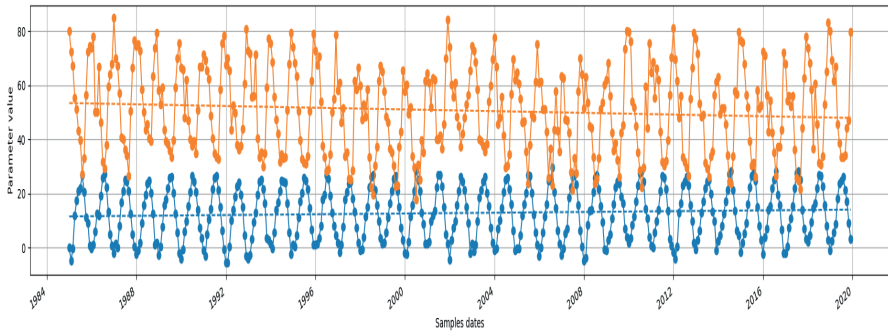


Figure 1. Temperature and Humidity Trend Graphs for Arapgir Station

Arapgir station is one of the stations where significant climatic changes have been detected in the study. A positive and statistically significant increase trend has been detected in temperature data for the period 1985–2019 with a confidence level of over 90%. Relative humidity data, on the other hand, showed a significant decrease with a confidence level of 94.1%. This situation reveals the existence of a clear warming and drying trend in Arapgir over the years. When evaluated visually, it is clearly observed in Figure 1 that the temperature curve rises over time, while the humidity curve shows a downward trend. The test results for the Arapgir station are presented in Table 1 along with other stations.

Such simultaneous increase in temperature and decrease in humidity indicates intensified evaporation processes and potential soil moisture reduction

in the region. These hydro-climatic alterations may increase drought sensitivity particularly in agricultural lands where irrigation demand is already high. Furthermore, long term warming signals may also influence snowmelt timing and seasonal runoff patterns in mountainous sub catchments surrounding Arapgir.

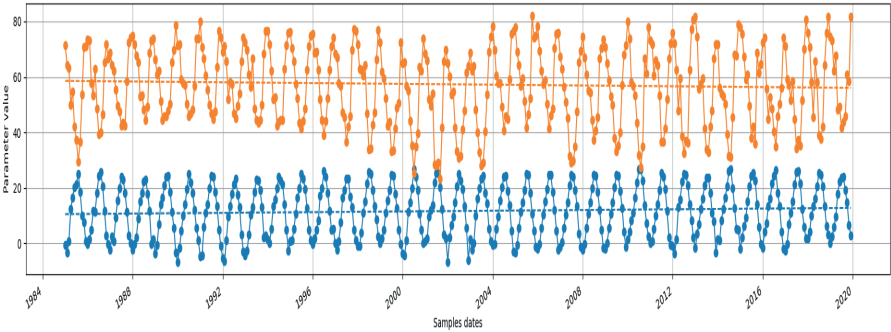


Figure 2. Temperature and Humidity Trend Graphs for Darende/Balaban Station

Both temperature and humidity data at the Darende/Balaban station showed directional changes, but these changes did not exceed the 90% confidence level, so no statistically significant trend was detected. As seen in Figure 2, there is a slight upward trend in the temperature curve, but this trend does not exhibit a consistent and strong structure. In the humidity graph, a fluctuating trend is observed over time. The trends identified at this station suggest that climate change is having a weak or stagnant effect. Numerical results can be accessed via Table 1.

However, the absence of statistically significant trends does not necessarily indicate climatic stability. In regions characterized by high interannual variability, weak trends may still lead to cumulative impacts on water resources and agricultural productivity. Local topographic controls, land use changes, and microclimatic circulation patterns may also contribute to the observed fluctuations in humidity values at this station.

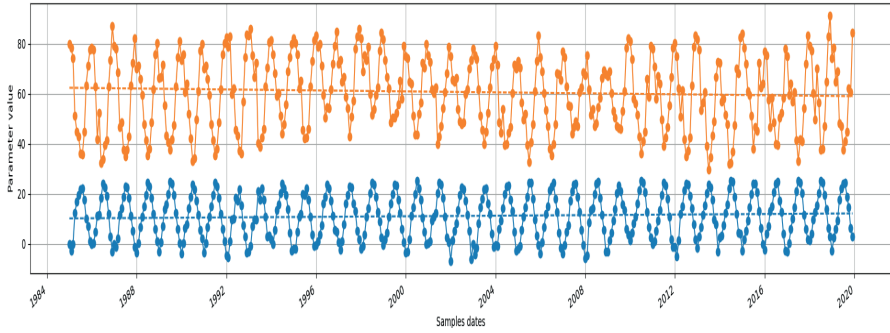


Figure 3. Temperature and Humidity Trend Graphs for Doğanşehir Station

Similarly, at the Doğanşehir station, the trends observed in temperature and humidity data were not found to be statistically significant. Figure 3 shows a general slight increase in temperature values, but this trend is not considered statistically significant. The humidity curve, on the other hand, shows irregular fluctuations. This situation may be due to the unstable microclimatic conditions at the station. Detailed statistical results are given in Table 1.

Irregular humidity variability combined with slight warming tendencies may influence evapotranspiration dynamics and crop water requirements in the Doğanşehir region. Such conditions may lead to increased uncertainty in seasonal water availability, particularly during dry years. Therefore, even non significant climatic tendencies should be monitored carefully within the framework of long term climate risk assessment.

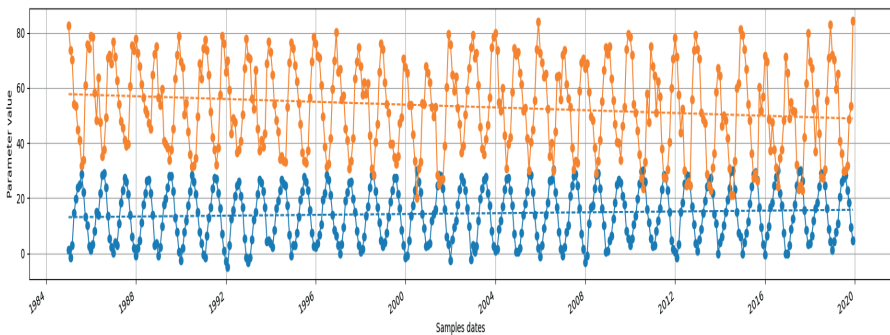


Figure 4. Temperature and Humidity Trend Graphs for Malatya Central Station

Malatya Central Station has been one of the stations where the effects of climate change have been most strongly observed. A positive and significant

increase trend has been determined in temperature data with a 92.5% confidence level. More strikingly, humidity data shows a significant decrease with a high confidence level of 99.8%. These trends are clearly observed in Figure 4; while temperature values have increased over the years, the humidity curve shows a distinct downward trend. These data indicate that the city center of Malatya has begun to be seriously affected by climate change. Numerical evaluations are presented in Table 1.

The stronger warming and drying signal detected in the urban station compared to rural stations may be associated with urban heat island effects, increasing impervious surfaces, and anthropogenic heat emissions. Rising temperature levels combined with declining humidity may significantly enhance urban flood vulnerability by altering rainfall intensity patterns and reducing infiltration capacity. Moreover, increasing thermal stress conditions may also have implications for public health and urban energy demand.

Table 1. Mann-Kendall test results and Sen’s Slope values for temperature and humidity data from four meteorological stations in Malatya province.

Station	Parameter	Z Value	p-Value	Confidence Level	Sen’s Slope	Trend
Arapgir	Temperature	+1.72	0.043	%90	+0.00196	Meaningful Increase
Arapgir	Humidity	-1.89	0.029	%94.1	-0.03785	Meaningful Decline
Darende/ Balaban	Temperature	+0.88	0.190	-	+0.00128	No Trend
Darende/ Balaban	Humidity	-0.75	0.226	-	-0.02254	No Trend
Doğanşehir	Temperature	+1.03	0.151	-	+0.00157	No Trend
Doğanşehir	Humidity	-1.20	0.116	-	-0.02916	No Trend
Malatya	Temperature	+1.79	0.036	%92.5	+0.00214	Meaningful Increase
Malatya	Humidity	-2.65	0.007	%99.8	-0.04837	Meaningful Decline

When the Mann Kendall MK test results and Sen’s Slope values presented in Table 1 are evaluated together it becomes clear that the temporal behavior of temperature and relative humidity varies among the meteorological stations in Malatya province. At the Arapgir station the calculated Z value of +1.72 and p value of 0.043 for temperature indicate a statistically significant increasing trend at the 90% confidence level while the Sen’s Slope value of +0.00196

suggests a gradual but persistent warming tendency on an annual basis. At the same station relative humidity results with a Z value of -1.89 and p value of 0.029 reveal a statistically significant decreasing trend at the 94.1% confidence level and the Sen's Slope coefficient of -0.03785 indicates that the rate of humidity decline is more pronounced than the rate of temperature increase.

In contrast at the Darende Balaban station p value results exceeding the 0.05 threshold for both temperature and humidity indicate statistically insignificant trends. However Sen's Slope values of +0.00128 and -0.02254 respectively imply the presence of weak directional warming and drying tendencies. Similarly at the Doğanşehir station Z values of +1.03 for temperature and -1.20 for humidity with corresponding p values of 0.151 and 0.116 fall below the statistical significance threshold yet the positive and negative slope coefficients suggest directional climate variability characterized by warming and drying signals.

At the Malatya Central station the temperature Z value of +1.79 and p value of 0.036 indicate a statistically significant increase at the 92.5% confidence level and the Sen's Slope value of +0.00214 represents the highest warming rate among the stations. More notably the relative humidity Z value of -2.65 and p value of 0.007 correspond to a very strong statistically significant decreasing trend at the 99.8% confidence level and the Sen's Slope coefficient of -0.04837 demonstrates that humidity decline is both statistically and quantitatively more pronounced than at other stations. Overall these results suggest that warming and drying tendencies are more strongly experienced particularly in urban and semi arid environments of Malatya province which may correspond to higher levels of hydro climatic risk.

When the statistical results of all stations are evaluated together it becomes evident that climate change impacts are not spatially uniform across the province. Significant temperature increases and relative humidity decreases detected at Arapgir and Malatya Central stations indicate stronger warming and drying tendencies in specific parts of the region. In contrast the absence of statistically significant trends at Darende Balaban and Doğanşehir stations suggests that climate variability patterns in these areas may be controlled by complex local topographic and microclimatic conditions. This spatial heterogeneity clearly demonstrates the importance of station based analysis approaches in regional scale climate assessments. These findings are consistent with the results reported by Avcı and Esen (2019) for Malatya Basin. In their study, temperature variables showed an increasing tendency while precipitation variables generally exhibited a decreasing tendency during the 1975-2017 period, and this pattern was projected to continue until 2040. They also

emphasized that annual mean temperature showed a statistically significant increase, whereas annual total precipitation showed a statistically significant decrease in Malatya. In this respect, the significant increase in temperature and marked decline in relative humidity detected at Malatya Central station in the present study support the broader regional picture of warming and increasing aridity in the basin.

The simultaneous increase in temperature and decrease in relative humidity represents an important hydro climatic alteration that may lead to enhanced evaporation rates and reduced soil moisture levels. Such processes may significantly increase drought risk especially in semi arid climatic environments and may exert pressure on agricultural water demand. Moreover rising temperature levels may influence snow accumulation and snowmelt dynamics resulting in changes in seasonal runoff regimes which may have critical implications for water resources sustainability. The local station based findings of the present study can also be interpreted within a broader regional drought framework. Ozocak et al. (2024) reported that in Türkiye, and particularly in parts of Eastern Anatolia, humid drought classes tended to decline while substantial changes were observed in near normal and moderately dry classes. For Malatya specifically, the innovative trend analysis results indicated an increase in the near normal class together with a decrease in moderately dry and very dry classes, revealing a spatial reorganization of drought conditions rather than a simple linear shift. Although the present study focuses on temperature and relative humidity rather than SPI based drought classes, the statistically significant warming and humidity decline observed at Malatya Central and Arapgir stations are consistent with the idea that the regional climate system is undergoing measurable hydro climatic change. Therefore, the current results should be interpreted not only as local atmospheric trends but also as part of a broader drought related transformation affecting Eastern Anatolia.

Furthermore the stronger trends observed at the urban Malatya Central station highlight the potential role of urban heat island effects and increasing impervious surface coverage on climate dynamics. These anthropogenic influences may reduce infiltration capacity and elevate urban flood risk levels during intense rainfall events. Therefore the findings provide important implications not only for meteorological variability but also for engineering planning drought management and sustainable water policy development.

Overall the spatial heterogeneity observed among stations indicates that local differences must be considered in the development of regional climate adaptation strategies. Supporting long term trend analyses with multiple

meteorological parameters and multi station datasets will contribute to more reliable prediction of future hydro meteorological risks.

4. Conclusions

This study revealed climatic trends in the region through Mann-Kendall and Sen's Slope analyses conducted using long-term temperature and humidity data obtained from four different meteorological stations in Malatya province. The combined use of these two methods made it possible not only to detect the existence of climatic trends but also to quantify their magnitude and direction in a robust manner. In this respect, the study provides a statistically supported evaluation of local climate change signals in Malatya province. The findings show that significant changes, such as temperature increases and humidity decreases, have occurred, particularly at the Arapgir and Malatya Merkez stations. According to Table 1, the Arapgir station exhibited a statistically significant increasing temperature trend with a Z value of +1.72 and a Sen's Slope value of +0.00196, while relative humidity showed a significant decreasing trend with a Z value of -1.89 and a Sen's Slope value of -0.03785. Similarly, Malatya Central station presented a significant temperature increase with a Z value of +1.79 and a Sen's Slope value of +0.00214, whereas the most pronounced humidity decline in the study was observed at this station with a Z value of -2.65 and a Sen's Slope value of -0.04837. These findings clearly indicate that warming and drying tendencies are especially evident in these two stations. Although certain trends were observed at the other two stations, these were not considered statistically significant. Nevertheless, the positive Sen's Slope values for temperature and the negative Sen's Slope values for humidity at Darende/Balaban and Doğanşehir stations suggest that weak warming and drying tendencies may also exist in these areas, even if they do not yet exceed the selected statistical significance threshold. This indicates that the absence of statistical significance should not be interpreted as the absence of climate variability, but rather as a sign of weaker or more spatially complex climatic responses.

Temperature increases, particularly during the summer months, lead to a decrease in humidity levels by increasing evaporation rates, which can have negative consequences for agriculture, drinking water supply, and ecosystem balance. Such hydro-climatic changes may also contribute to reductions in soil moisture, increases in irrigation demand, and growing pressure on surface and groundwater resources. In semi-arid environments such as Malatya, these processes may intensify drought vulnerability and create additional challenges for sustainable water management. The high-confidence temperature increase

and humidity decrease observed at the Malatya Central station, in particular, indicate that the urban heat island effect and climate change are felt more intensely at the city level. The stronger warming and drying signal at Malatya Central may be associated with urban expansion, increasing impervious surfaces, and anthropogenic heat emissions, all of which can amplify local climate stress. This suggests that urban areas may face greater risks in terms of thermal discomfort, water demand, and climate-related infrastructure pressure in the future. Similar trends in Arapgir reveal that rural areas are also significantly affected by these effects. The results from Arapgir further demonstrate that climate change impacts are not limited to the urban environment, but are also reflected in rural settings where agriculture, soil water balance, and ecosystem stability are highly sensitive to atmospheric moisture conditions.

This study demonstrates the importance of regional climate analysis. Even within the boundaries of a single province, different climatic responses can be observed at different stations. The spatial heterogeneity revealed by the statistical results highlights that local topography, land use characteristics, elevation differences, and microclimatic factors can strongly influence the manifestation of climate trends. Therefore, local and station-based observations remain essential for understanding the true character of regional climate change. Therefore, increasing station-based assessments in future studies will pave the way for healthier decision-making processes for both planners and climate policy developers. Future studies may benefit from incorporating additional climatic variables such as precipitation, evaporation, soil moisture, and wind speed, as well as seasonal and monthly sub analyses, in order to obtain a more comprehensive understanding of hydro-climatic variability in the region. In addition, combining statistical trend analyses with drought indices and remote sensing based observations may provide a more integrated framework for evaluating future climate risks. Additionally, the findings obtained serve as a scientific basis for the design of drought early warning systems, the development of water management policies, and the determination of regional adaptation strategies. In this context, the present study offers a useful scientific reference for engineering applications, regional planning, agricultural adaptation, and climate policy development in Malatya province. Overall, the results suggest that the province is experiencing a gradual but measurable warming and drying process, and that this process should be carefully monitored in order to reduce future hydro-meteorological and socio-economic risks.

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CHAPTER 5

ERZURUM PROVINCIAL CENTER DRINKING WATER NETWORK SYSTEM AND COST BENEFIT ANALYSIS

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Burak ÇIRAĞ³

Abstract

This study examines the drinking water network system in the central district of Erzurum. The drinking water requirement of the provincial center was calculated and compared with the current amount of drinking water used, and the water loss rate was calculated. Investigations conducted in some neighborhoods identified different problems in different areas. At the same time, cost comparisons were made between the profit obtained from the reduction in operating costs due to the reduction in the water loss rate in the drinking water network system and the cost of a sample network renovation project to be carried out in a selected neighborhood in the city center. Due to the decrease in the water loss rate in the drinking water used, the amount of treated water

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will decrease, resulting in a reduction in the amount of chemicals used. As a result, an average annual savings of 9,700,000 TL was achieved in chemical expenses. The approximate cost of the sample network renovation project was calculated to be approximately 5,200,000 TL. Based on the calculations, when comparing the daily amount saved due to the decrease in drinking water usage with a drinking water network renewal project of 5,800 meters, as in the example project, it was determined that the profit from 196 days is equal to the cost of the example project. When the daily savings are calculated on an annual basis, it is seen that they correspond to an average annual cost of 10,600 meters of network renovation.

1. Introduction

Water is the cornerstone of all living life on Earth. About 60% of the human body is composed of water, and this ratio can vary depending on factors such as age, gender, and physical structure. Water plays a direct role in countless biological functions, from digestion to circulation, temperature regulation to the elimination of toxins. In this context, access to clean and reliable drinking water sources is a vital necessity for human health and the well-being of societies. However, access to drinking water is unfortunately not provided equally for every individual worldwide. According to United Nations data, approximately 2 billion people today do not have regular access to safe drinking water; this situation poses significant problems in terms of health, education, and economic development (World Health Organization, 2015). Factors such as the rapidly increasing population, rapid urbanization, pollution caused by industrial activities, and global climate change are both threatening water resources and significantly reducing water quality. The salty water of the oceans constitutes approximately 97% of the global water. The remaining 3% is freshwater, of which approximately 69% is used as a freshwater source. 30% of glaciers are found in karst and porous aquifers, while the rest are in surface water (lakes, rivers, streams, and wetlands, etc.). Freshwater is the fundamental substance of life on Earth and is increasingly diminishing. 75% of Europeans and 33% of the world's population use groundwater as their primary drinking water source. However, in many countries, both the quantity and quality of this resource have been jeopardized by humans. Today, water scarcity affects 88 developing countries, which corresponds to half of the world's population (Howard and Gelo, 2002). Especially the pressure on groundwater reserves and surface water sources (lakes, rivers, dams) is increasing day by day, which further highlights the importance of sustainable water management. When considering that water is indispensable not only for individual health but also for sectors such as agriculture, energy production, and industry, the protection

and conscious use of drinking water sources have become a priority issue on a global scale. The main types of drinking water sources (groundwater and surface water sources), the environmental and human-induced threats these sources face, the importance of water at both individual and societal levels, and the water crisis are some of the most important topics in this regard.

Turkey, although it appears to be a water-rich country geographically, faces serious problems in terms of the distribution and use of water resources. Despite an average annual rainfall of 450 billion cubic meters, the country's usable water potential reaches approximately 112 billion cubic meters per year. However, only 57 billion cubic meters of this potential can be utilized (DSI 2023). In Turkey, the supply of drinking and utility water is provided from surface and underground sources. According to the analyzes conducted, approximately 59.5% of the sources used for drinking and domestic water are obtained from surface waters, while 40.5% are sourced from underground waters. In metropolitan areas, however, these ratios vary; for example, 75% of the drinking water in Antalya and Konya comes from underground sources, while 60% of Izmir's drinking water is sourced from underground. This situation, especially with the decline in groundwater levels, paints a worrying picture in terms of sustainable water supply. The distribution of water resources in Turkey shows significant regional differences. For example, although the Marmara Region has a high population density, the water resources in this region constitute only 4% of the total water flow. This imbalance makes it difficult to manage water efficiently and fairly. Turkey's drinking water sources are facing serious threats in terms of both quantity and quality. At the forefront of these threats are overuse, pollution, and climate change. Sustainable water management and conscious water use are critically important to overcome these issues. The stage that should be prioritized in the conscious use of water resources is the drinking water supply systems we use today. Excessively treated and used drinking water, uncontrolled water losses, faulty network systems, and incorrect practices applied to these network systems lead to the excessive use of water resources. In our country, as well as in various parts of the world, many efforts have been made to combat water loss, with some being successful while others continue to work toward their desired goals. When we look at the world as a whole, we see that in some developed countries, water loss rates are even below 10%, but in some countries, this rate is above 60% (Leakage in the Water Industry: Ofwat, 2018). Today, humanity uses many resources around the world. We see that all the resources being used have an alternative. However, water has never been a resource with an alternative. From our bodies to every part of our planet, water, which is at the very center of life, will always be an irreplaceable factor for humanity. Therefore, the conscious

use of water resources and their sustainability is the most important factor for the future of our world.

Karakaya and Toprak (2018) have accurately calculated both physical and administrative water losses in all 81 provinces of our country using the ZFT algorithm they developed. They have also determined that the drinking water loss rate is high across Turkey. In their study, they found that the average water loss rate across Turkey is around 47%. At the same time, it has been noted that there are regions with very high levels of water loss, such as 71%. Fırat et al. (2021) conducted a study on the analysis of the performance of water utilities in terms of managing water losses and the development of key performance indicator calculation tools. With their study, detailed analyzes of the values jointly accepted by the International Water Association (IWA) and other organizations were conducted, and the most ideal ones for loss water management were determined. In order to monitor and calculate these identified values in a planned and systematic manner, a web-based “Non-Revenue Water Basic Performance Analysis Calculation Tool” has been developed. It has been stated that this web-based calculation tool will assist in the management performance analyzes of water loss management and the components causing water loss, monitoring, and the development stages of leakage control-detection studies.

From this study, the amount of drinking water used in the center of Erzurum was reduced, and the ratio of the chemicals used in the drinking water treatment facility was calculated. At the same time, a region in need of renewal of the drinking water network was selected from the city center, and a sample drinking water network renewal project was drawn up. The approximate cost value of the prepared project has been calculated and compared with the values obtained from drinking water treatment.

2. Material and Methods

Estimated cost of sample project

The cost of a planned network renewal project in the city center of Erzurum will be compared with the cost of the excess water treated daily. When determining the area for the sample project, the areas with the oldest infrastructure lines in the city center were taken as the basis. In the city center of Erzurum, it is observed that the greatest difficulties regarding the drinking water network are experienced in the areas that are historically and residentially old. In this context, due to being one of the oldest settlements in Erzurum and its central location, a network renewal project will be developed in the

area between Çaykara Street and Mumcu Street, and a cost analysis will be conducted based on this area (Figure 1).



Figure 1. Satellite image of the project area

If we calculate the approximate cost of the drinking water network renewal work to be carried out within an area of approximately 160,000 m² between Mumcu Street and Çaykara Street at 2025 prices (Figure 2, Table 1);

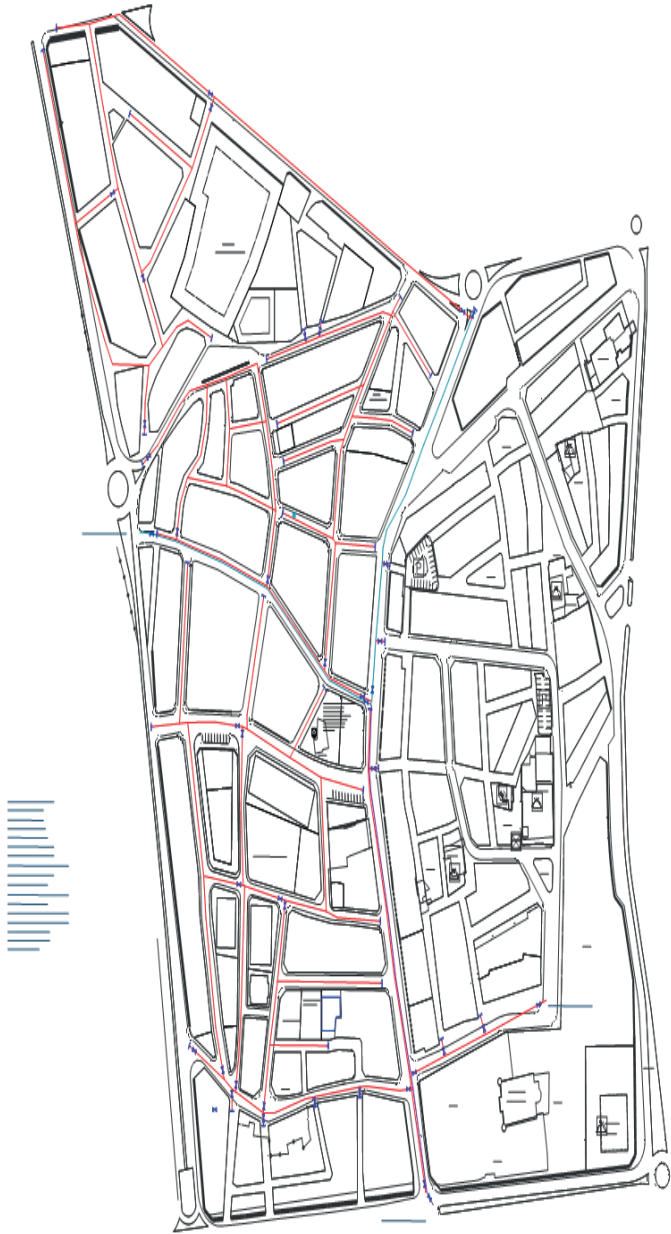


Figure 2. Mumcu Drinking Water Project

Table 1. Materials to be used in the sample project

Material	Quantity	Current Price
Reduction from Ø315 to Ø160	1 unit	6,584.00 TL
Ø315 PE pipe including workmanship	300 meters	2503 TL
Ø160 including workmanship	500 meters	691 TL
Ø110 including workmanship	5000 meters	346 TL
Ø315 valve including workmanship	1 unit	55,172 TL
T from Ø315 to Ø110	4 unit	6551 TL
T from Ø315 to Ø160	1 unit	7053 TL
T from Ø160 to Ø110	3 unit	576 TL
Ø110 T	47 unit	586 TL
Ø110 valve	34 unit	9841 TL
Ø160 valve	4 unit	16,555 TL
Excavation	5800 meters	490 TL
Backfill	5800 meters	643 TL

Ø300 300m, Ø160 500m, Ø110 5000m PE drinking water pipes, approximately 6000m of excavation and filling operations, and valves and connection elements for line connections are required. The project site measurements were made using a GPS device, and the project was drawn using the NetCAD program. A reduction from Ø315 to Ø160 is one of the pipe connection elements used to decrease or increase the diameter of the existing pipeline. Reduction, in its literal sense, means “diminution.” In our project, one reduction from Ø315 to Ø160 will be used. The current unit price is 6,584.00 TL.

Ø315, Ø160, Ø110 pe (10 atü) drinking water pipes were connected to the Ø315 line at the point where the 500 line on Cumhuriyet Avenue intersects with Mumcu Avenue at the beginning of the project. The 315 line progresses along Mumcu Street, supplying only the left side area. In the places corresponding to each street, 110 exits have been made from the Ø315 line. After approximately 300 meters with the Ø315 line, one end continues to Çaykara Street, while the other end continues for about 500 meters from the lower Mumcu area to Kazım Karabekir Street with the Ø160 line. The supplies to all the side streets on the project are also provided by a Ø110 line. The total length of the 100 mm line used is approximately 5000 meters.

Valves should be used in specific areas to intervene in the drinking water on the line as needed. A total of 39 valves have been used in the project, including 1 valve of 315, 4 valves of 160, and 34 valves of 110. Fittings (T) are a type of pipe connection fitting known as fittings. It is T-shaped and has

two outlets at a 90-degree angle from the main line connection. The pipe has a side outlet and it is only a small portion. Use a pipe T-piece to connect the pipes, even at a right angle. Pipe fittings, such as pipe tees, are frequently used. They come in various sizes and coatings and are made from different materials. To transport two-phase liquid mixtures, pipeline networks often use pipe tees. In drinking water lines, tees are used as additional parts for side street distributions, subscriber distributions, and areas where the line is divided into two. A total of 55 tee pieces will be used in the project. T-pieces have been used at the entrances of the side streets located between Mumcu Street and Çaykara Street. The T-pieces used in the project are based on their diameters; excavation and filling operations are carried out according to the diameters of the pipes in the drinking water supply and network lines. The excavation depths also vary according to the climatic conditions of the region where the project is being carried out. During the excavation process, the excavation depths are carried out below the frost level according to the region's climate.

In our project, approximately 5800m of excavation work will be carried out. The PE drinking water pipes, which are welded after excavation, will be laid inside the line. After the placement of the pipes, the backfilling process should be partially done by hand. To prevent the machine from leaving hard material on top of the pipe, the casing process must be done manually. Therefore, the filling should be paid in two different positions. The part done by hand should be billed separately from the part done by machine (Figure 3).



Figure 3. Drinking water pipeline excavation

In drinking water networks and transmission lines, PE pipes leave the factory in the form of 100-meter coils or 13.5-meter strips and arrive at the construction site. Therefore, the pipes need to be joined together during the

installation process. During the joining process, trimming and butt welding operations are performed (Figure 4).



Figure 4. Drinking water distribution system components

Drinking water treatment cost calculation

Drinking water treatment plants are facilities that purify water obtained from natural sources (surface water, groundwater) thru physical, chemical, and biological processes to make it suitable for human consumption. The main goal is to make the water colorless, odorless, tasteless, microbiologically safe, and compliant with international drinking water standards (Figure 5).



Figure 5. Erzurum Drinking Water Treatment Plant

The criteria for drinking water quality have been determined by the World Health Organization (WHO), the European Union (EU), the United States Environmental Protection Agency (EPA), and the Ministry of Health in Turkey. The applicable regulation in our country is the “Regulation on Waters for Human Consumption” (2005, rev2023). Among the parameters are pH, turbidity, microbiological values (E. coli, coliform), heavy metals, and pesticides. In drinking water treatment plants, the cost of treating 1 cubic meter (m^3) of water varies depending on the size of the facility, the technology used, the quality of the raw water, and the energy and chemical expenses.

TÜİK (2022) Municipal Water Statistics and İSKİ (2023) 2023 Activity Report. According to the data from the Istanbul Water and Sewerage Administration, the costs of drinking water treatment generally range from 2 to 5 TL/ m^3 for conventional treatment methods. In advanced treatment technologies (ultrafiltration, activated carbon, etc.), the cost ranges from 5 to 10 TL/ m^3 . In advanced treatments using technologies like reverse osmosis, this cost can reach levels of 10 - 25 TL/ m^3 .

While energy costs account for approximately 25-40% of total expenses, the use of chemical substances ranges from 15-25%, and personnel and maintenance costs vary between 10-20%. These ratios are more evenly distributed in central treatment plants established in metropolitan areas, reducing unit costs.

ISKI Example: According to the 2023 activity report of the Istanbul Water and Sewerage Administration, the average cost of treated drinking water in Istanbul has been stated as 3.50 TL/ m^3 . This value is low compared to the Turkish average and reflects the impact of economies of scale. If the size of the Erzurum drinking water treatment plant is considered to be much smaller than the İSKİ treatment plants, the cost of drinking water treatment will be higher. Looking at the Erzurum Water and Sewerage Administration’s 2024 activity report, we see that the budget for the Water Treatment Plants Department for 2024 is approximately 205 million TL (ESKİ 2025). When compared to the İSKİ example, 15% of the expenses should be for the chemicals used in the treatment of drinking water. When we compare the value of 30 million, which corresponds to 15%, with the activity report, we see that the chemical substance expenses are 35 million. This shows us that the unit costs of large-scale treatment plants are lower. There is an annual chemical procurement cost of 35 million TL. The cost of the chemical used to treat the 7200 m^3 of water used per hour would be 5000 m^3 /hour if the water loss is 25%. The drinking water requirement for the center of Erzurum is 4000 m^3 /hour, and the current water usage is 7200 m^3 /hour. If we achieve a 25% water loss rate, our hourly water gain will be $7200 - 5333 = 1867 \text{ m}^3$. If we consider approximately 2000 m^3 ,

when we look at the cost of chemical substances, it is 35,000. 000 TL, if used for 7200m³/hour water, for 2000m³/hour water, a profit of 9,722,222 TL would be achieved. 222 TL annual profit is achieved. This provides an average daily income of 26,636 TL.

3. Results and Discussions

Currently, the losses in drinking water supply and transmission systems are causing serious problems both economically and environmentally. Therefore, the renewal of urban networks, the reduction of loss and leakage rates, and the more efficient use of resources are of great importance. In this study conducted specifically in the province of Erzurum, the current state of the drinking water network was examined in detail, and the potential savings that could be achieved by reducing the identified water losses were calculated. Additionally, the approximate cost of the renovation work to be carried out in a sample neighborhood was determined, and this cost was compared with the daily earnings. The obtained data clearly show that infrastructure investments provide economic benefits in the long term. All cost calculations have been derived from the current 2025 unit prices of the Municipalities Bank and the Ministry of Environment and Urbanization. The details of the cost calculation for the work area are provided below (Table 2):

Current unit prices of the pipes used:

$$\text{Ø315 total} = 2212 + 291 = 2503 \text{ TL per meter} \times 300 \text{ meters} = 750,900.00 \text{ TL}$$

$$\text{Ø160 total} = 571 + 120 = 691 \text{ TL per meter} \times 500 \text{ meters} = 345,500.00 \text{ TL}$$

$$\text{Ø110 total} = 272 + 74 = 346 \text{ TL per meter} \times 5000 \text{ meters} = 1,730,000.00 \text{ TL}$$

$$\text{Total pipe cost} = 2,826,400.00 \text{ TL}$$

Valve costs to be used:

$$\text{Ø315 valve total} = 53,128 + 2,044 = 55,172 \text{ TL per unit} \times 1 \text{ unit} = 55,172 \text{ TL}$$

$$\text{Ø160 valve total} = 15,888 + 667 = 16,555 \text{ TL per unit} \times 4 \text{ units} = 66,220 \text{ TL}$$

$$\text{Ø110 valve total} = 9,391 + 450 = 9,841 \text{ TL per unit} \times 34 \text{ units} = 334,594 \text{ TL}$$

$$\text{Total valve cost} = 455,986.00 \text{ TL}$$

Fittings used in the project according to their diameters:

$$1 \text{ unit reduction from Ø315 to Ø160} = 6,584.00 \text{ TL}$$

$$4 \text{ units tee from Ø315 to Ø110} = 6551 \text{ TL per unit} \times 4 = 26,204 \text{ TL}$$

$$1 \text{ unit tee from Ø315 to Ø160} = 7053 \text{ TL per unit} \times 1 = 7,053 \text{ TL}$$

3 units tee from Ø160 to Ø110 576 TL per unit = $576 \times 3 = 1,728$ TL

47 units Ø110 tee 586 TL per unit = $586 \times 47 = 27,542$ TL

Total = 69,111.00 TL

Current unit prices for excavation and backfilling Works:

Composite trench excavation without shoring 77.84 TL per m³

Manual foundation and trench backfill 412.10 TL per m³

Machine backfill using excavated material for foundation and trench 231.10 TL per m³

For Ø315 pipe:

Excavation = $0.85 \times 300 \times 1.70 \times 77.84 = 33,744$ TL

Backfill = $[(0.85 \times 300 \times 0.60) - (3.14 \times 300 \times 0.157 \times 0.157)] \times 412.10$
= 53,482 TL

Backfill = $0.85 \times 300 \times 1.10 \times 231.10 = 64,823$ TL

Total = 152,049 TL

For Ø160 pipe:

Excavation = $0.60 \times 500 \times 1.40 \times 77.84 = 32,693$ TL

Backfill = $0.60 \times 500 \times 0.30 \times 412.10 = 37,090$ TL

Backfill = $0.60 \times 500 \times 1.10 \times 231.10 = 76,263$ TL

Total = 146,046 TL

For Ø110 pipe:

Excavation = $0.60 \times 5000 \times 1.30 \times 77.84 = 303,576$ TL

Backfill = $0.60 \times 5000 \times 0.30 \times 412.10 = 370,890$ TL

Backfill = $0.60 \times 5000 \times 1.00 \times 231.10 = 693,300$ TL

Total = 1,367,766 TL

Total excavation and backfill cost = 1,665,861.00 TL

Butt fusion welding:

For Ø315 pipe:

Unit price of butt fusion welding = 1,817 TL

Unit price of facing = 498 TL

Butt fusion welding = 1,817 TL per unit $\times 23$ units (300 13.5) = 41,761.00 TL

Facing = 498 TL per unit $\times 23 \times 2 = 22,908.00$ TL

For Ø160 pipe:

Unit price of butt fusion welding = 1,170 TL

Unit price of facing = 254 TL

Butt fusion welding = 1,170 TL per unit $\times 38$ units (500 13.5) = 44,460.00 TL

Facing = 254 TL per unit $\times 38 \times 2 = 19,304.00$ TL

For Ø110 pipe:

Unit price of butt fusion welding = 979 TL

Unit price of facing = 176 TL

Butt fusion welding = 979 TL per unit $\times 50$ units (5000 100) = 48,950.00 TL

Facing = 176 TL per unit $\times 50 \times 2 = 17,600.00$ TL

Total cost = 194,983.00 TL

Table 2. Cost breakdown

Pipe cost	2,826,400.00 TL
Valve cost	455,986.00 TL
Fitting cost	62,527.00 TL
Excavation and backfill cost	1,665,861.00 TL
Butt fusion welding and facing cost	194,983.00 TL
Total	5,205,757 TL

Network renewal and improvement activities require significant costs. In this study, the total cost of the renovation operations carried out for the project taken as an example has been determined to be 5,212,341.00 TL. The total cost includes a pipe expense of 2,826,400.00 TL. For the trimming and butt welding of the pipes, 194,983.00 TL was spent, the cost of the valves was 455,986.00 TL, and the cost of the additional parts was calculated to be 69,111 TL. Additionally, the cost of excavation and backfilling work for the drinking water lines has amounted to 1,665,861.00 TL. As a result of all these works related to the sample project, the total cost reaches 5,212,341.00 TL. The planned example renovation project in the drinking water network systems in Erzurum corresponds to this cost when evaluated according to a long-term cost-benefit analysis. As a result of reducing water losses, a daily gain of 26,636 TL is achieved. If water loss is reduced to the targeted level, the savings achieved within 196 days would be equivalent to the cost of

approximately 5,800 meters of drinking water line. Thanks to the daily profit of 26,636 TL, it is possible to carry out a renewal of 10,670 meters in one year. Renewals of drinking water networks on a city scale reduce treatment costs and increase investment budgets.

4. Conclusions

In this study, the cost of renovating the drinking water network system in Erzurum province was calculated by selecting a sample neighborhood. The cost calculation obtained was compared with the profit amounts gained from the drinking water treatment system. According to the cost analysis conducted, the pipe cost alone was determined to be 2,826,400.00 TL, making this item the largest portion of the total investment cost. For the welding and machining operations, 194,983.00 TL was spent, and this item is a significant expense to meet the technical requirements of the renewal process. The expenses for valves and fittings amounted to 455,986.00 TL and 69,111.00 TL, respectively; these items are critical for ensuring the safety of control and connection points on the network. The total cost of excavation and filling works is 1,665,861.00 TL, indicating that infrastructure works are highly costly in terms of logistics and labor. The total cost of these items amounts to approximately 5,212,341.00 TL, which indicates that it is an investment that can be recouped within 196 days with a daily saving of 26,636 TL achieved by reducing water losses. For the rehabilitation of the network, a comprehensive renewal strategy should be implemented in priority areas, taking into account the age of the existing pipelines, the materials used, and the level of deformation. Especially pipes older than 30 years should be gradually replaced. Within the framework of smart water management, SCADA (Supervisory Control and Data Acquisition) systems can be established to detect instantaneous flow, pressure, and leaks. For regional measurement and pressure control, DMA (District Metered Area) systems should be used to divide the network into areas, and areas with high loss rates should be monitored specifically. By controlling the pressure, stress on the pipelines can be reduced, preventing leaks. Urbanization plans should be aligned with the routes of the water network. Especially in new residential areas, infrastructure projects should be prepared with the principle of sustainability. Municipalities and water authorities should establish periodic maintenance and inspection programs; field workers should receive regular training. Regulations should be regularly updated, and legal incentive mechanisms aimed at reducing water losses (such as rewarding those who report leaks) should be implemented. Additionally, academic and technical collaborations established between universities, local governments, and the private sector can both strengthen technical infrastructure and increase the efficiency of implementations.

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